Arnold Schwarzenegger
Governor

GOVERNMENT ACTIONS AND INNOVATION IN CLEAN ENERGY TECHNOLOGIES:

THE CASES OF PHOTOVOLTAIC CELLS, SOLAR THERMAL ELECTRIC POWER, AND SOLAR WATER HEATING

PIER PROJECT REPORT

Prepared For:
California Energy Commission
Public Interest Energy Research Program

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), conducts public interest research, development, and demonstration (RD&D) projects to benefit California's electricity and natural gas ratepayers. The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

In 2003, the California Energy Commission's Public Interest Energy Research (PIER) Program established the **California Climate Change Center** to document climate change research relevant to the states. This Center is a virtual organization with core research activities at Scripps Institution of Oceanography and the University of California, Berkeley, complemented by efforts at other research institutions. Priority research areas defined in PIER's five-year Climate Change Research Plan are: monitoring, analysis, and modeling of climate; analysis of options to reduce greenhouse gas emissions; assessment of physical impacts and of adaptation strategies; and analysis of the economic consequences of both climate change impacts and the efforts designed to reduce emissions.

The **California Climate Change Center Report Series** details ongoing Center-sponsored research. As interim project results, the information contained in these reports may change; authors should be contacted for the most recent project results. By providing ready access to this timely research, the Center seeks to inform the public and expand dissemination of climate change information, thereby leveraging collaborative efforts and increasing the benefits of this research to California's citizens, environment, and economy.

Government Actions and Innovation in Environmental Technology for Power Production: The Cases of Photovoltaic Cells, Solar Thermal Electric Power, and Solar Water Heating is the final report for the Preliminary Economic Analyses of Climate Change Impacts and Adaptation, and GHG Mitigation project (contract number 500-02-004, work authorization number MR-006) conducted by the Goldman School of Public Policy at the University of California, Berkeley.

For more information on the PIER Program, please visit the Energy Commission's website www.energy.ca.gov/pier/ or contract the Energy Commission at (916) 654-5164.

Table of Contents

List of Tables

List of Figures

Abstract

This report explores the dynamics of policy design and innovation in photovoltaic cells, solar thermal electric power, and solar water heating. These three "solar" technologies are important examples of greenhouse gas-reducing technologies. Their importance is not merely because of their future potential in supporting the development of a carbon-neutral energy system, but because they provide an opportunity to observe the way policy supporting technological innovation and organizational behavior have played out in the past. Through a detailed policy history, a treatment of major technological innovations and market developments, and a combination of complementary quantitative and qualitative metrics of innovation, this report arrives at several implications for future policy design. These policy implications consider inventive activity, knowledge transfer activity, learning-by-doing, and other aspects of the innovation process—as well as strategic behavior by firms, ranging from technology designers to system installers. In addition, there is some attention to the treatment of technological change in climate models.

Keywords: Photovoltaic, solar thermal electric, STE, solar water heating, SWH, technological innovation, clean energy technologies

Executive Summary

Introduction

Technological innovation is critical to the cost-effective stabilization of greenhouse gas concentrations in the atmosphere at levels that avoid "dangerous anthropogenic interference with the climate system," as called for in the United Nations Framework Convention on Climate Change. The level of technological change required and the number of economic sectors that emit greenhouse gases makes it highly unlikely that one technology will be a "silver bullet" to solve the climate change problem. It is also unlikely that the needed technologies will be developed with no public intervention. Although the literature on innovation shows the primacy of the private sector as a source of innovation, it also shows that the private sector underinvests in research and development (R&D) when compared to the societal returns of that R&D.

The technologies that either control or prevent greenhouse gas emissions ("environmental technologies") are developed not just in response to competitive forces; they are also advanced, to a considerable extent, by specific government actions. These actions include: creating (and destroying) demand for various technologies through regulation; conducting and supporting R&D activities in support of environmental goals; promoting technologies through subsidy; and facilitating knowledge transfer between government, regulated firms, and outside environmental equipment suppliers through everything from the patent system to industry-specific conferences, publications, and collaborations.

Purpose

Although the government has an important role to play in supporting the kinds of innovations necessary to achieve climate policy goals, there is little empirical evidence about the relative effectiveness of different government actions at inducing innovation in climate-relevant technologies. This study helps to fill this empirical gap through an analysis of government actions and innovation in three environmental technologies with relevance to greenhouse gas abatement: (1) photovoltaic (PV) cells, (2) solar thermal electric power, and (3) domestic solar water heating.

Project Objective

This project's objective was to derive "lessons learned" about past experience with government support and technological innovation in these three solar energy technologies. For this study, *innovation* was understood to be a process that incorporates a number of different activities—including invention, adoption/commercialization, diffusion, and post-adoption innovation such as learning-by-doing—with outcomes such as improvements in cost and realized performance. The researchers used complementary, established, and repeatable quantitative and qualitative research methods that have been employed successfully by the principal investigator in previous studies of innovation in clean energy technologies. Specifically, this project systematically integrated analyses of

U.S. patents, public research laboratory activity, technology conference proceedings, experience curves, and interviews with influential experts.

Project Outcomes

Photovoltaic (PV) Cells

Since the first commercial cell was introduced, PV cells have improved considerably: costs have declined by a factor of 100 since the 1950s, and the electrical efficiency of commercial cells has doubled since the 1970s. Yet the technology remains expensive relative to both conventional power generation and renewables such as wind and solar thermal electric technology. With the exception of a few niches, diffusion has been trivial; worldwide cumulative installed capacity amounts to the equivalent of a few large coal-fired plants. Still, with production growing at 40 percent per year and continuing cost reductions, interest in future innovation in the technology is strong and governments around the world, including California, are actively engaged in supporting invention and diffusion in PV cells.

Three observations stand out about the effect of policy on innovation in PV cells. First, R&D spending was important to PV development. Second, there has been a shift in inventive activity away from the United States and toward Japanese inventors, in part because of a stronger combination of R&D and demand-side policies in Japan. This raises the possibility that a similar combination of R&D and demand-side policies in the United States might drive invention by U.S. firms, bringing with it complementary economic benefits. Support for this viewpoint includes the finding that California's leadership in clean energy technology policy has corresponded with a disproportionately high patent share in PV, solar thermal electric, and solar water heating technologies in contrast to its share of overall U.S. patents. On the other hand, Germany has a similar combination of policies and has a weaker patenting position than both the U.S. and Japan.

The third observation is that learning-by-doing by system installers may provide an important opportunity for PV cost reduction, and government policies may well create that opportunity if designed correctly. Indeed, policy makers anticipate that technological improvements, as realized in cost reductions and performance improvements, will accompany support of PV diffusion. This is not always the case, however. In the "solar profiteer" case, for example, in which firms enter a subsidized market to exploit it and then get out, the performance of installed technologies do not improve. In the "white-elephant" case, in which rebates to consumers make consumers less sensitive to price, overall system prices rise. There is possibly evidence for this in two recent PV cases: prices of installed PV systems in California increased in 2001 when buydown rebates were increased to $4.50/watt (W), while prices in Germany increased over the past few years as tariffs greater than 50¢/kilowatthour (kWh) were guaranteed.

Options for avoiding these pitfalls include subsidies that either pay for performance (¢/kWh) or are based on verification of operation.

Solar Thermal Electric Power

Government actions have influenced the development of solar thermal electric power technology at all stages of the innovation process, from federal R&D in the 1970s that established heliostat design (a fundamental solar thermal electric enabling technology) to inducing a surge in orders for new construction planned for 2006 and 2007. Perhaps most notably, government actions have facilitated incremental innovations in commercially installed technology that resulted in significant operating and maintenance cost reductions. Not a complete success, government actions have at times been a barrier to the diffusion of solar thermal electric technologies. In addition, government actions in support of solar thermal electric do not appear to have stimulated as much (or as diverse) public knowledge transfer as in the other two cases.

Experts state that three government actions were crucial for incremental innovations in commercially installed solar thermal electric technology to occur. First, the 1978 Public Utility Regulatory Policies Act created a foothold in the electricity generation sector for small, independent energy producers. Second, California's standard offer contracts—especially the 1983–1985 interim Standard Offer Number 4 (ISO4) contract, which essentially guaranteed an effective tariff of $0.12 per kWh for ten years—provided some assurance of future earnings to these producers. Third, collaborative R&D between Sandia National Laboratories and the only firm in the world to commercialize solar thermal electric at the time Luz was successful in identifying significant opportunities for operating and maintenance improvements in the company's nine "Solar Electric Generating System" plants, which were built in California between 1984 and 1990.

Despite successfully supporting innovation in solar thermal electric technology, policy has at times been an important barrier to the increased diffusion of this technology (and any corresponding innovative improvements in costs and performance). For example, the limitation on maximum plant size in the Public Utility Regulatory Policies Act regulations hindered efforts at cost reductions, as plants were not built at their optimal scale. In addition, the large investments (> $100 million) needed to build solar thermal electric plants meant that the technology could not compete effectively with certain advanced conventional generating technologies during the 1990s and early 2000s, at a time when federal and state electricity deregulation constrained the competitive playing field to the market value of electricity generation, unadjusted for environmental benefits. Renewable portfolio standards in different states, especially those with solar set-asides, and policy efforts in other countries are now fostering considerable investment in solar thermal electric, with dozens of new commercial plants scheduled for completion in the next few years in Nevada, Arizona, Spain, and elsewhere.

Finally, there is little doubt from the innovation literature that more diverse pathways for knowledge exchange advance innovation (for an example, consider "open source" code), but many firms play their innovation cards "close to the chest" because of proprietary concerns. This tension is particularly troubling in technologies with large public good characteristics like clean energy technologies. Solar thermal electric technology appears to exhibit this tension with underperformance in such knowledge transfer metrics as patenting activity, papers in technical conferences, and ties among organizations of different types (such as universities, non-utility firms, and government organizations). This may be one reason why experts consider the role federal R&D played in identifying and codifying the improvements made in the Solar Electric Generating System plants for use in other installations to be “crucial” to the development of the technology. Certainly, this role was crucial to sustaining the technology after Luz went bankrupt in 1991.

Solar Water Heating

Solar water heating technology experienced a burst of innovative activity in the late 1970s and early 1980s. Inventive activity was intense, the technology improved, and diffusion of units into the market was rapid and substantial. However, in the mid-1980s this burst of activity ended as rapidly as it began. Since then, solar water heating innovation in the U.S. has been stagnant, with only a tiny market served by a few small firms. Government actions played a major role in causing the boom, the bust, and the long period of stagnation.

Three observations stand out about the effect of policy on innovation in solar water heating technology. First, this rapid and brief diffusion was correlated with government actions. Second, the innovations considered most important by experts related more to learning-by-doing in the installation of systems than to innovations in solar water heating technology per se; experts believe that these innovations were not particularly rapid, in part due to the implications for markets and skilled labor of policy failures for solar water heating. Third, past policy failures have made it difficult for new efforts to take hold in creating U.S. markets for solar water heating, despite the cost-competitiveness, reliability, and greenhouse gas advantages of this technology.

There are at least four policy implications from the problems incurred in the boom and bust phenomenon in solar water heating technology. First, there is an inherent danger in designing policies that provide incentives for installation rather than performance. The boom in the diffusion of solar water heating systems did not have as comparatively a strong role in offsetting natural gas and electricity for heating water as might be expected because many of the systems did not work well and were abandoned within a few years (some claim that half of the installed systems were no longer functioning after five years). An incentive to counteract the danger of a low-performance boom in a technology is to tie capital cost incentives to system performance verification, as in the successful case of policy support for solar water heating in Hawaii, in which each system undergoes an inspection that costs less than $50 to conduct.

Second, solar water heating demonstrates the adverse effects of allowing the sudden and premature expiration of policies that support an environmental technology. In the industry busts that can accompany these events, considerable loss of technology-related knowledge can occur in both the private and the public sector.

Third, the perception of technical unreliability is problematic for public efforts that support diffusion of an emerging environmental technology, particularly if the audience familiar with the reliability problems is large. Although technical improvements have overcome many of the problems with early solar water heating systems, the perception of solar water heating as technically unreliable persists both among policy makers and consumers.

Finally, a fourth policy implication from the solar water heating case is that policy intermittency and uncertainty undercuts innovation, and subsidies have been a particularly unstable policy instrument. Thus, subsidies may be best to avoid for supporting innovation unless they can be guaranteed to last over at least modest timeframes.

Conclusions and Implications for Models

This research indicates that the outcomes of innovation with respect to performance and cost improvements are not standard across these and other climate-relevant technologies (this is documented in this report in the shape of “experience curves” that relate innovative outcomes to the diffusion of a number of environmental technologies studied by the principal investigator). In addition, this research makes clear that government actions have played an important role both in fostering the development of these three solar energy technologies as well as in unintentionally creating barriers to certain aspects of that development. These findings complicate the important policy-relevant task of modeling technological innovation for the purposes of forecasting greenhouse gas emissions and mitigation costs.

1.0 Introduction

Technological innovation is critical to the cost-effective abatement of greenhouse gas (GHG) emissions. The government has an important role to play in support of the kinds of innovations necessary to achieve climate policy goals. In economic terms, this role is justified by the fact that these innovations are driven, to a significant extent, by the provision of the public good of a "clean" (or GHG-reduced) environment. In many cases, they also help provide the public good of national security through their contribution to energy independence. The weak (if any) incentives for private investments to provide public goods are likely to intensify existing trends, well-known in the economics of innovation literature, of private industry's underinvestment in research, development, and demonstration (RD&D), as compared to the societal returns of that RD&D (see Griliches 1992; Jones and Williams 1998, for example). As a result, innovations directed to abating GHGs are developed in a strategic environment in which government plays an important role.

In California, carbon dioxide (CO_2) is the most prominent of the GHGs; even without imported electricity in the calculation, 83% of California's GHG emissions is CO_2 from fossil fuel combustion, a percentage that has held quite steady between 1990 and 2002 (Bemis and Allen 2005). There are three basic technology strategies that can be used to reduce CO_2 from fossil fuel combustion. The first is to keep the combustion process the same while controlling emissions; this can be done either through pre-combustion interventions such as fuel switching (for example, from coal to natural gas), or through post-combustion interventions such as carbon capture and sequestration. The second is to keep the combustion process the same but reduce demand for the power that results from combustion; this can be done either through encouraging greater efficiency in end-use devices or by meeting some of this demand for power in end-use devices with alternatives to fossil-fuel fired generation (for example, domestic solar water heating). The third strategy is to generate power with alternatives to fossil fuels, such as water, wind, and the sun. These three basic strategies hold, no matter the end-product of the fossil fuel combustion, be it transportation (41.0% of California's CO_2 emissions in 2002), industry (20.7% of CO_2 emissions), or electric power (19.5% of CO_2 emissions) (Taylor 2006).

This report is the second retrospective analysis of government actions and innovation in environmental technologies with relevance to GHG abatement to be sponsored by the California Energy Commission's Public Interest Energy Research (PIER) program. The technologies focused on in the first report, selective catalytic reduction (SCR) technology for nitrogen oxides (NO_x) control from stationary power plants, and wind power, provide examples of the first technology strategy (SCR controls emissions from traditional combustion activities) and the third technology strategy (wind power is an alternative generation technology). This second report focuses on three solar technologies: photovoltaic (PV) cells, solar thermal electric (STE) power, and domestic solar water heating (SWH). These three technologies provide examples of the second technology strategy (SWH is an end-use technology that fosters independence from the power generated by traditional combustion) and the third technology strategy (PV and STE are alternative generation technologies).

In both reports, the same research approach is used to explore the effectiveness of government actions on both the process and outcomes of innovation in these technologies. This approach is a systematic integration of analyses of U.S. patents, public research laboratory activity, technology conference proceedings, experience curves, and interviews with influential experts. These complementary and repeatable quantitative and qualitative methods—as well as the distribution across technology strategies of the cases studied in the first and second report—support a comparative understanding of the environmental innovation process. To take advantage of this methodological strength, reference will be made to findings in the first report during the discussion chapter of this report.

This report has five chapters. In addition to laying out the rationale for this study, this introductory chapter explains the selection of the case technologies investigated. It also chronicles the main federal, state, and international government actions of relevance to the three cases, with attention to both public investments in the various technologies, as well as policy instruments that have supported their diffusion. Finally, this chapter provides an overview of the innovation process and the main methodologies employed in later chapters.

The next three chapters focus on each technology separately, discussing technical and market developments and displaying the results of the various analyses. Note that the government actions of relevance to each technology will not be detailed in these case-specific chapters, as there is considerable overlap between the relevant policy histories for each technology; distinctions for unique technologies will be made, as appropriate, in the introductory chapter.

The concluding chapter provides synthesis across the cases, as well as some thoughts on the implications of this material for climate policy in California.

1.1. Selection of Case Studies

For many years, "solar" technologies referred not only to technologies powered directly from the sun's energy, but also to technologies powered indirectly from that energy, including wind power, tidal power, and biomass power (relying as it does on the photosynthesis conducted by plants). To some extent, therefore, policies to support solar energy technologies can be thought of as representative of policies to support almost all alternative/renewable power technologies. But this definition of solar, and the large number of government actions that would be relevant to these technologies, is unwieldy for a single report using multiple methods to address. At the other extreme, focusing on a single solar technology to understand the interplay between government actions and innovation in climate-relevant technologies would miss important aspects of that interplay.

Direct solar application technologies can be subdivided as (1) photoelectric or (2) solar thermal applications, which either generate electricity or displace fossil-fuel generation at the point of end-use. At the peak of federal research and development (R&D) funding of solar energy technologies, budgets were more-or-less evenly divided in support of: (a) PV cells, which generate power via the photoelectric effect; (b) STE power, a solar thermal generating application; and (c) solar heating and cooling (including domestic SWH technologies), which apply solar thermal principles to displace fossil fuel generation at the point of end-use. Figure 1 illustrates federal R&D for direct solar technologies from the 1970s through 2002.

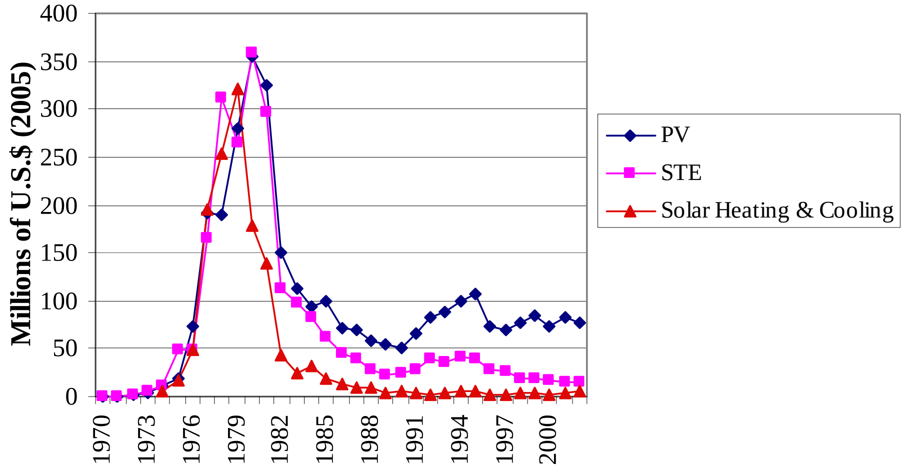

Figure 1. Solar R&D in the United States, 1970–2002

Source: (IEA 2006)

What explains this shift? Simple indicators like comparative levelized cost and market penetration do not fully address this question. Table 1, for example, shows recent estimates of the levelized costs of various fossil fuel and renewable generation technologies. Note that STE technologies generate electricity at a lower cost than PV, but provide a smaller percentage of world generating capacity. Meanwhile, domestic SWH is used in 2.5% of worldwide households (Martinot 2005).

The relative complexity of the technologies is likely to be a factor in this, as is a changing emphasis within government on what is the best strategy and most appropriate rationale for investing in R&D, based on the perceptions of investments and payoff times held by various political actors according to their underlying values. But without juxtaposing these technologies against each other, these and other insights would not become analytically apparent, and potential lessons for government support of climate-relevant technological innovation could be missed.

In the effort to avoid this pitfall, this report chooses to focus on government actions and innovation in direct solar energy technologies with a “Big S.”: PV cells, STE power technologies, and domestic SWH technologies. Although not a comprehensive investigation of solar technologies, it is hoped that this more manageable set of technologies will provide insights that will be representative of some of the successes and failures that might be predictable in various GHG-reducing technology policy pathways that government might pursue going forward.

Table 1. Levelized costs of electricity by various technologies

		(Badr and Benjamin 2003) ¢/kWh [*]	(Martinot 2005) ¢/kWh	(IEA 2005) ¢/kWh [†]	% of World Capacity [‡]
Power Generation					
Fossil Fuels	Coal	-	-	3.50–6.00	24.40
	Natural gas combined cycle	5.18	-	4.00–6.30	21.20
	Natural gas simple cycle	15.71	-		
Renewables/Other	Large hydro	6.04	3.00–4.00	-	18.95
	Nuclear	-	-	3.00–5.00	6.50
	Wind	4.93	4.00–6.00 [**]	4.50–14.00	1.26
	PV	42.72 (50 MW plant)	20.00–40.00 (rooftop PV)	-	0.11 [††]
	STE (trough)	21.53 (13.52 w/natural gas; 17.36 w/thermally enhanced storage)	12.00–18.00	-	0.01
Hot water/heating					
	Solar hot water/heating	-	2.00–25.00	-	2.50 % of households

* At 10.8% discount rate.
† At 10% discount rate.
‡ Fossil fuel and nuclear capacity figures are through the end of 2003 IEA (2005), while the rest are through the end of 2004 (Martinot 2005).
** This is the on-shore wind estimate. Off-shore wind is 6–10¢/kWh.
†† This percentage is combined off-grid plus grid-connected capacity. Grid-connected capacity alone is 0.05%.
Note: "-" indicates that the report gives no clear estimates for this technology.
Source: (Badr and Benjamin 2003; IEA 2005; Martinot 2005)

1.2. Government Actions to Promote Solar Technologies

Government actions related to solar energy technologies are of two types: either direct support of the development of the technologies or indirect support of their development by fostering relevant markets.

The first type of action, primarily public funding of RD&D of various technologies, is conducted either by government actors or private and nonprofit entities. It is sometimes known in the literature as "supply-push" or "technology push."

The second type of action, often referred to as “demand pull” or “market pull,” supports the diffusion of the technology in hopes that that diffusion will reach a tipping point that will allow it to continue without public support. In recent years, there has been recognition in environmental policy circles that with increased diffusion can come the cost and performance improvements that often accompany the maturation of a technology, either through economies of scale or post-adoption innovative activities such as learning-by-doing. This latter innovative activity emerges from resolving the unexpected problems that often arise in the transition from bench- or pilot-scale technology to commercial scale technology. Demand-pull policy instruments employed in the past in support of solar energy have included: government procurement programs; commercial and residential building codes; commercial and residential financing mechanisms such as tax credits, rebates, buy-down programs, and net metering; and renewable portfolio standards in which a legislatively established percentage of a state’s generation must be attributed to renewable sources.

The history of solar energy policy that follows is grouped by time period—before 1970, the 1970s, the 1980s, and the 1990s/2000s—and according to U.S. federal, California, and international government actions (the international government actions will focus primarily on Japan and Germany). Where relevant, both supply-push and demand-pull instruments will be highlighted. Note that because government does not play a particularly strong role in the first time period, before 1970, the distinctions between federal, state, and international actions are not made in this section.

1.2.1. Before 1970

Solar energy technologies—particularly solar thermal applications—have a long history, which a number of authors trace back as far as the architecture and writings of the ancient Greeks, and later, Romans. Xenophon is credited as the first to record the principles of passive solar heating, while Archimedes used the concept of burning mirrors as a weapon and the Roman Pliny developed the solar furnace (Butti and Perlin 1980). In the United States, evidence of architecture using passive solar design principles date as far back as an aboriginal shelter in 3,000 B.C., as well as Anasazi settlements circa 1,100 A.D. (Hempel 1983). Photoelectric applications do not have as long a history, as the photoelectric effect was only observed in 1839, during Edmond Becquerel’s experiments with an electrolytic cell which generated more electricity when exposed to light (DOE 2006).

Much of the very early work on solar energy technologies was therefore not related to government actions, but rather to individual scientists and entrepreneurs. Those government actions that did occur were not easily catalogued as “technology push” or “demand pull,” but rather, of protecting individual rights. For example, in the 6th century A.D., the Justinian Code established the first “sun rights” to ensure that buildings had access to the sun; this type of government action recurred, particularly in “solar access rights” established in the 1970s (see California’s AB 3250 and AB 2321 in 1978, for example) (Hempel 1983).

One of the earliest American solar energy pioneers was John Etzler, who in 1833 released America’s first blueprint for solar energy use. In his book, he proposed constructing “burning mirrors” which could automatically track the sun’s movement while focusing its energy on specially insulated boilers that would produce steam energy. He also proposed solar stills to desalinate seawater, as well as a rudimentary flat-plate collector (Hempel 1983, p. 49).

Etzler wrote before the power consumed in the United States was predominantly generated by fossil fuels, which occurred for the first time in the mid-1880s (as shown in Figure 2). The trend toward increased dependence on coal for power was evident before that, however, and just as increased dependence on oil generated warnings about resource exhaustion in the twentieth century (most notably, the peak oil curve presented to the American Petroleum Institute in a paper by Marion King Hubbert [Hubbert 1956]), similar warnings were issued about a possible exhaustion of coal in the nineteenth century. Most influential among these was a book published in 1865 by W. Stanley Jevons (Jevons 1865), which inspired the solar thermal engine development work done by John Ericsson, the designer of the celebrated iron battleship, "The Monitor." Ericsson, in turn, inspired Aubrey Eneas, who built his first solar steam engine, which automatically tracked the sun, in 1898 (Halacy 1973). In 1901, Eneas displayed his engine, used to pump water, in Pasadena, California (Halacy 1973, pp. 45–47). Other early solar engines in the United States included those installed by H. E. Willsie and John Boyle, Jr., in Needles, California, in 1905 and by Frank Shuman in Tacony, Pennsylvania, in 1907 and Cairo, Egypt, in 1912 (Butti and Perlin 1980, pp. 110–11). Only the Shuman engine in Egypt proved cost-effective, but World War I, Shuman's death, and oil and gas strikes in sunny areas around the world combined to stop increased commercialization (EIA 2001).

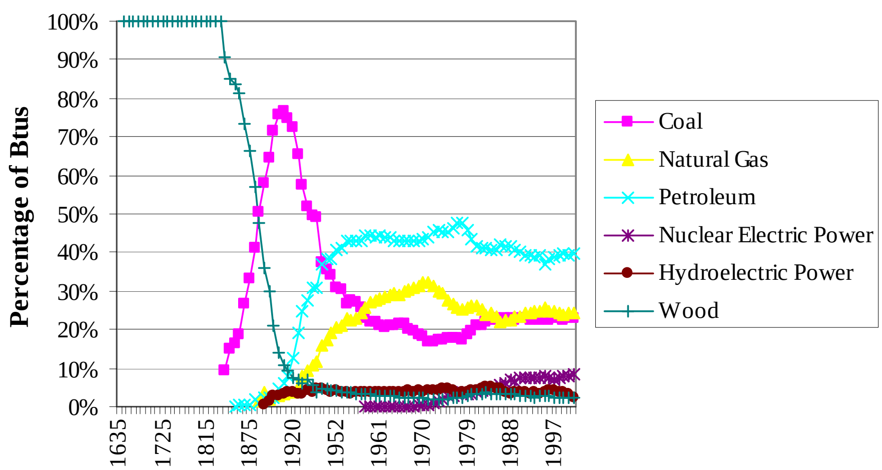

Figure 2. U.S. energy consumption by fuel, 1635–2001

Source: Adapted from (Hempel 1983)

At the time Eneas displayed his engine in Pasadena, the city had almost one-third of its homes outfitted with solar water heaters (Butti and Perlin 1980). Clarence M. Kemp patented the nation's first commercial solar water heater, the "Climax," in 1891, and two Pasadena businessmen, E. F. Brooks and W.H. Congers, bought the rights from him to manufacture and sell it in California in 1895 (Laird 2001, p. 20). The popularity of the

Climax led to competing and improved designs (i.e., the “Walker Solar Heater,” the “Improved Climax,” and the “Day and Night”), the diffusion of the SWH into Arizona, and repeated sales of the manufacturing rights in California (ibid.). The Day and Night sold for the first time in 1909 in Monrovia, California, by William J. Bailey, ultimately forced the Walker and Climax manufacturers out of business (ibid. pp. 129, 136). Day and Night heaters diffused into states such as Arizona, New Mexico, and Hawaii (a booming business was born in Florida through sale of the rights to H. M. “Bud” Carrothers in 1923), and in 1920 they reached their sales peak of 1,000 systems in a single year (ibid. pp. 139, 143). Before succumbing to competition from big discoveries of natural gas in the Los Angeles basin in the 1920s and manufacturing stopped in 1941, over 7,000 Day and Night heaters had been sold (ibid. p. 141).

California lost the lead in SWH to Florida by the mid-1930s. Charles F. Ewald, who had taken over Carrothers’ financial affairs after Miami’s housing boom collapsed and the city was devastated by a hurricane in 1926, improved on the Day and Night’s design and patented the “Duplex” (Laird 2001 pp. 144–148). Between 1932 and 1934, the Duplex revived the SWH business in Florida. Demand for SWH in Miami multiplied with New Deal legislation passed in late 1934 guaranteeing low-interest mortgage rates and home improvement loans (ibid. pp. 148–151). This (inadvertent) demand-pull legislation inspired a rush of Duplex competitors to enter the market by copying the expired Day and Night patent. Some of these new entrants cut costs in ways that resulted in leaking roofs and too little hot water, prompting another type of government action, a quality assurance one designed to protect consumers (ibid, pp. 151–2). The Federal Housing Administration, which had financed most of the solar heaters, sent an investigator to check claims against some of the manufacturers, and the manufacturers responded by voluntarily adopting manufacturing standards (ibid. p. 152). The industry continued to thrive: 80% of the homes built in Miami between 1937 and 1941 were outfitted with SWH; sales of solar water heaters were double those of traditional heaters in Miami in 1941; and public housing projects in other southern states adopted SWH as well (ibid.).

A government ban on non-military uses of copper in World War II halted the industry for a period (ibid. p. 154). But many of the Florida companies rebounded, only to face new problems, including: existing customers wanting larger capacities of hot water; bursting tanks due to corrosion caused by electrochemical reactions between copper and iron components in the system; increased costs tied to increased copper prices and wages; and increased competition by electric heaters, which began to benefit from economies of scale. Few solar water heaters were sold after the late 1950s (ibid. p. 155).

Concerns about a potential oil shortage were prominent in the late 1940s, with the United States becoming a net oil importer in 1948 (Hempel 1983, p. 81). With the beginning of the Korean War in 1950, energy shortages became prominent topics at cabinet meetings (ibid., pp. 20–22). A congressional mandate led to President Truman creating a National Security Resources Board in1947, and the President’s Materials Policy Commission (otherwise known as the Paley Commission, after chair William S. Paley) in early 1951 (ibid., p. 27, p. 24). The overall findings of the 1952 Paley Commission report were that energy shortages were inevitable because of shrinking reserves of oil and natural gas and expected cost issues with coal, and that the United States should not become too dependent on oil from the Middle East because it should not be counted on during wartime. It was recommended that these shortages should be addressed on the supply side through a transition to solar and nuclear energy that should begin before 1975, although it would be generally cheaper to reduce demand (Laird 2001, p. 47).

Although not integrated throughout the report, the Paley Commission's chapter on solar energy called for large increases in funding for solar research (Hempel 1983, p. 96). Note that this implies that some solar research was ongoing at the time, but according to Laird, "the numbers floating around in the literature" for government R&D funding for solar energy in the 1940s, 1950s, and 1960s "are contradictory and often without references to reliable primary sources" (Hempel p. 207). Hempel quotes Dr. George Löf testifying before Congress that federal R&D spending on solar development in 1960 were "a few hundred thousand dollars" (Hempel 1983, p. 88). Laird cites figures from the 1963 Federal Council for Science and Technology report, *Research and Development on Natural Resources*, for direct solar energy R&D (not hydropower, wind, or biomass) in fiscal year (FY) 1962 of $1.7 million and FY 1964 of $5.4 million (ibid., p. 52). As he points out, this is in direct contradiction to the $100,000 per year figure "many people quoted in the 1970s" (ibid. p. 207). This uncertainty is why Figure 1 begins in the 1970s.

The Paley Commission report was not followed up on by the new Eisenhower administration, an advocate of minimal government intervention in markets, except perhaps as it pertained to nuclear power. In part this was due to fossil fuel prices, which declined for almost two decades after 1952. In part, this was due to excitement about nuclear technology, which benefited from government support of its dual role as both a military and a civilian application. In 1954, groundbreaking occurred for the first U.S. demonstration nuclear power plant, constructed in Shippingport, Pennsylvania; the ceremony was attended by Eisenhower (Gazit 1999).[1] Then in 1955, the Atomic Energy Commission announced a new public-private partnership program to develop nuclear power plants, a supply-push instrument that solar energy was not to benefit from until much later (Hempel 1983, p. 96). By 1960, federal nuclear R&D was one-thousand times the level of solar R&D, according to Löf (Halacy 1973, p. 57).

During the same year that groundbreaking occurred on the Shippingport reactor, a major breakthrough occurred in the development of photovoltaic cells. In 1954, the "typical efficiency of commercial photocells" was 0.5% (Halacy 1973, p. 75). In a paper written that year by D. M. Chapin, C. S. Fuller, and G. L. Pearson (Chapin et al. 1954), the solar battery they developed in their work with silicon p-n junctions had an efficiency of 6% (ibid). This Bell Telephone Laboratories discovery was quickly adopted into the earliest U.S. satellites, including the first successful U.S. satellite, the Vanguard TV-4, in 1958, which used six solar panels to power its radio transmitter (Halacy 1973, p. 77). By 1965, the newly minted National Aeronautics and Space Administration (NASA), created in 1958 from the National Advisory Committee for Aeronautics and other government agencies, used almost a million solar batteries per year (Beattie 1997, p. 26).

While NASA funded photovoltaic research, the National Science Foundation (NSF) funded various solar thermal applications, to a limited extent. In 1968, Congress

[1] This plant later became the first full-scale nuclear power plant in the United States, in 1957.

authorized the 18-year-old NSF to initiate a more applied research program than its traditional mission. The resulting program, Interdisciplinary Research Relevant to Problems of Our Society (IRRPOS), was unconventional not only for its applied focus, but also for the requirement that for a proposal to be accepted, it should have a participant who would act as a potential implementer if the research paid off. End-users were expected to "provide financial or in-kind support" (Beattie 1997, p. 31). IRRPOS had a modest budget that included projects in energy and the environment; in 1971, it was expanded and renamed Research Applied to National Needs, or RANN, and became the lead agency in charge of solar energy research, for a time.

1.2.2. 1970s

The 1970s were unique, as a decade of great activity in support of solar energy technologies at the federal, state, and international levels. In large part, this was because of the two oil shocks that happened in this decade (the first began on October 17, 1973 and the second began in the spring of 1979), which highlighted the importance, already of growing concern to lawmakers, of reducing dependence on foreign oil suppliers. But there was also an emerging environmental awareness that occurred in this decade, which saw the birth of a number of fundamental environmental laws and institutions.

Federal: There were three main types of federal government actions regarding solar energy technologies in the 1970s: organizational changes regarding the conduct of research and development, a number of supply-push actions, and a few demand-pull actions. In 1973, the Federal Energy Office was established. This organization absorbed a number of previous agencies, and was itself absorbed in 1974 into the new independent executive agency, the Federal Energy Administration (FEA). In 1975, the Energy Research and Development Administration (ERDA) was established, and absorbed earlier agencies (particularly the Atomic Energy Commission [AEC]). Then in 1977, FEA, ERDA, and other agencies were consolidated into the cabinet-level Department of Energy (DOE).

All of these changes affected energy R&D in general, but there were additional organizational developments that were particular to solar energy. In August 1973, NSF's RANN program became the lead agency for the terrestrial solar energy program over NASA, which maintained its solar R&D program for space and aeronautical systems.

ERDA took over this leadership role in 1975 (for more information, see Larson and West 1996, pp. 80–4). In anticipation of this, as well as concerns that the new ERDA would be dominated by a nuclear power focus due to the AEC it was swallowing, in 1974 three government actions were passed that were designed to provide direction and momentum for solar energy R&D as part of a balanced energy R&D portfolio.[2] These actions, which represent technology-pushes to some degree, were the Non-nuclear Energy Act of 1974, P.L. 93-577 (8/74); the Solar Energy Research, Development and Demonstration Act, P.L. 93-473; and the Solar Heating and Cooling Demonstration Act, PL 93-409 (9/11/74) (Larson and West 1996, pp. 90–2).

[2] This R&D included resource studies, which at least one author—Janet L. Sawin—has categorized as demand pull, as they facilitated the diffusion of renewable energy technologies (see Sawin 2001 p. 116).

Within ERDA, the FEA was considered the lead agency on solar commercialization activities. To enhance this role, the Energy Policy and Conservation Act of 1975 (EPCA), PL 94-163 (12/22/75), gave the FEA "certain pricing and regulatory authority for use in promoting conservation and fuel switching" and the Energy Conservation and Production Act of 1976 (ECPA), PL 94-385, further expanded its role (Beattie 1997, pp. 82–3).

ERDA later centralized its solar energy R&D function in the Solar Energy Research Institute (SERI), which was authorized under the 1974 Solar Energy Research, Development and Demonstration Act, P.L. 93-473.[3] After twenty proposals were considered regarding its location, ERDA established SERI at the Midwest Research Institute site in Golden, Colorado, in 1977 (it became the National Renewable Energy Laboratory (NREL) in 1991). This was considered the "national" SERI, but four "regional SERIs," known as the Regional Solar Energy Centers (RSECs), were also established in 1977 in Massachusetts, Georgia, Minnesota, and Oregon, with vague ties to the Colorado SERI (for more information on the RSECs, see Larson and West 1996, pp. 675–690; Beattie 1997, pp. 83, 128–31, 150–52).

The RSECs were shut down in March 1982, in part due to Congressional criticism since their founding about mission overlap with SERI and in part due to Reagan administration hostility to energy R&D. During their brief four years of operations, they primarily worked on commercialization activities (particularly information dissemination) that leveraged federal funds with state funds. The Mid-America Solar Energy Complex (MASEC, in Minnesota) was particularly involved in creatively promoting the acceptance of active and passive solar home designs; the Northeast Solar Energy Center (NESEC, in Massachusetts) concentrated on PV applications; the Southern Solar Energy Center (SSEC, in Georgia) focused on SWH; and the Western Solar Utilization Network (Western SUN) coordinated all energy policy for its region (Hempel 1983, p. 154).

The year 1978 was a tremendous one for solar energy technology interests, both as a political movement and legislatively. As a political movement, May 3, 1978, was declared Sun Day, "a national observance of the sun's promise as a practical source of energy" (Lotker 1991, p. 17). On that day, special events were held in almost every state and major city to promote solar energy technologies, and President Carter went to SERI to give an address. In his address, Carter announced the transfer of $100 million from nuclear and coal R&D into solar R&D in the fiscal year 1979 budget, and he directed "his administration to prepare an intensive Domestic Policy Review (DPR) on solar energy" (ibid., p. 156).

Legislatively, 1978 saw the passage of the National Energy Act (NEA), the first federal action that could really be seen to have strong demand-pull elements for solar energy technologies. The NEA consisted of five pieces of legislation.

First, it contained the Public Utility Regulatory Policies Act of 1978 (PURPA), Pub. L. No. 95-617, 92 Stat. 3117 (codified as amended in scattered sections of Titles 15, 16, 26,

[3] After the DOE was established, Sandia National Laboratories in Albuquerque, New Mexico was chosen to head the federal research program in solar thermal technologies, and provided the test site for later demonstrations.

42, and 43 U.S.C.A.). Section 210 of PURPA (Cogeneration and Small Power Production) removed grid-related barriers to independent energy producers, known in PURPA as qualifying facilities (QFs). PURPA created two classes of QFS: cogenerators, which "had no size (MW) limits but had to meet certain standards regarding energy utilization efficiency" and small power producers (SPPs) (Sawin 2001, p. 106). SPPs:

> "had restrictions regarding fuel source (generally limited to renewable or waste fuels) and, also, had a maximum size limit of 80 MW to be a QF and a limit of 30 MW for exemption from regulation as a utility under state law as well as under PUHCA [the Public Utility Holding Company Act of 1935]. In addition to these limitations, both classes of QF's had to meet certain other restrictions such as a 50% limitation on utility ownership." (ibid.)

PURPA mandated that utilities pay for power from QFs at "avoided costs," or the costs saved by not having to build new power plants, as well as sell back-up power to QFs at non-discriminatory rates. A Federal Energy Regulatory Commission (FERC) ruling in 1980 established "avoided costs" to mean a utility's full avoided costs—versus its average system costs—and required utilities to provide data on present and future costs of energy on their systems (Larson and West 1996, p. 95). It is worth noting here that avoided costs could be calculated at the time of delivery or when a contract was signed, even if the costs based on the contract date were higher than those at the time of delivery. This was later upheld by the Supreme Court (ibid).

The FERC ruling on PURPA also required utilities to make all necessary interconnections to facilitate energy sales, and "with some exceptions, required that utilities purchase all QF electric energy and capacity regardless of the utilities' needs" (ibid.). State utility commissioners were charged with implementing the FERC rules on PURPA within one year; many states (not including California) were not generous in the computing of avoided costs under PURPA. Much of PURPA was delayed until the early 1980s because of legal issues involving state interpretations.

The second piece of legislation in the NEA with relevance to solar energy technologies was the Energy Tax Act of 1978 (ETA), Pub. L. No. 95-618, 92 Stat. 3174 (codified as amended in scattered sections of Titles 26 and 42 U.S.C.A.). The ETA included both residential energy income tax credits for SWH equipment expenditures (30% of the first $2,000 and 20% of the next $8,000, up to a cumulative maximum of $2,200) and business energy tax credits (10% for investments in solar, wind, geothermal, and ocean thermal technologies) (Larson and West 1996, p. 95). The ETA was passed while there was a pre-existing federal tax credit of 10% on all capital investments across industrial sectors in order to spur economic recovery.

Third, the NEA contained the National Energy Conservation Policy Act (NECPA), PL 95-619 (11/9/78), an information dissemination measure imposed on the utilities in order to promote energy efficiency and the technologies and businesses engaged in residential solar and wind power (Hempel 1983, p. 151). In addition, NECPA:

> "authorized up to $100 million over three years for solar retrofits and demonstrations in federal buildings; authorized low-interest loans for homeowners installing solar measures, up to a maximum of $100 million

> to be allocated through the Government National Mortgage Association; authorized up to $98 million over three years for federal purchases of PV systems for use in federal installations; granted states federal monies in support of solar and conservation retrofits in schools, hospitals, and other public buildings (the grants were to cover up to 50% of costs incurred)" (Larson and West 1996)

The final two pieces of the NEA did not contain significant solar provisions. The Power Plant and Industrial Fuel Use Act, PL 95-620 (11/9/78) was designed to promote fuel-switching by major energy consumers, primarily away from oil and natural gas to coal, although other alternative sources, including solar, benefited as well (Hempel 1983, p. 151). And the Natural Gas Policy Act, PL 95-621 (11/9/78), which accelerated gas price deregulation, effectively raised natural gas prices to the consumer, thereby making substitutes (including solar) more economically attractive (for more information, see Margolis 2002).

Two other pieces of federal legislation relevant to solar passed in 1978, outside of the NEA. First, Congress passed the Solar Photovoltaic Research and Development Act, P.L. 95-590, which authorized $125 million in funding for the National Photovoltaic Program in fiscal year 1979, and recommended a hefty budget of $1.5 billion over the next ten years (Sawin 2001, p. 114). The law particularly encouraged PV commercialization and cost-cutting R&D (Hempel 1983, pp. 163–4). Second, the Small Business Energy Loan Act, P.L. 95-315, created a solar energy loan program (up to $500,000 for installing and operating solar energy technologies) within the Small Business Administration (Hempel 1983, p. 167).

By the end of 1978, Carter's staff had completed his Domestic Policy Review of solar energy, which he acted on in June 1979, on the occasion of dedicating a SWH system on the roof of the White House. He announced a national goal, proposed in the DPR, of meeting, by 2000, 20% of the nation's energy demand with solar energy technologies (Hempel 1983, p. 189). He also announced four modest new incentives to help the United States toward that goal: (1) a Solar Bank to provide low-interest loans for residences and commercial buildings, thereby subsidizing part of the solar market not incentivized by existing tax credits (i.e., subsidies for low-income people, residents in multi-family dwellings, and people investing in passive solar energy systems); (2) tax credits for builders incorporating passive solar into home designs; (3) a 25% tax credit for solar technologies providing industrial process heat; and (4) a 15% tax credit for wood stoves (ibid., pp. 163–4, 204–5). All but the industrial process heat tax credit were defeated or left unfunded by Congress (ibid., p. 165).

On a number of energy matters, 1979 was a difficult year. The Shah of Iran was overthrown in January and the "second oil shock" began in the spring. The Three Mile Island nuclear meltdown occurred in March. And the Organization of the Petroleum Exporting Countries (OPEC) announced a 15% price increase shortly after Carter's solar announcement. These events helped convince Carter that more needed to be done to relieve energy problems in the short term, which solar development wouldn't really accomplish. Conservation, although effective, was politically unpopular as it was seen as "going without" rather than being more efficient (Bereny 1977, p. 245). On July 15, Carter announced five new measures, none of which involved solar energy. Most prominent of these measures was the establishment of an Energy Security Corporation for producing synthetic fuels from coal and oil (Synfuels), to be funded by a windfall profits tax on oil companies. The other measures were: (1) the establishment of an Energy Mobilization Board to facilitate bringing new non-nuclear production online; (2) imported oil quotas; (3) a request for standby authority from Congress to ration gasoline; and (4) "new measures for cutting oil consumption by utilities" (ibid., p. 168).

California: According to an excellent dissertation tracing the history of the solar movement through 1983, during the 1970s, "state-level solar bureaucracies – particularly in California – were fast becoming major solar policy arenas, often supplanting federal initiatives" (Sawin 2001).

The origins of this in California can be traced back to 1974, when California passed AB 1575, the Warren-Alquist Act, which established a broad energy program including research and accelerated development of solar energy (Sawin 2001, p. 170). AB 1575 also started a new institution, the State Energy Resources Conservation and Development Commission, otherwise known as the California Energy Commission (Energy Commission), which opened its doors in 1975 (Hollon 1980, pp. 14–15; Talbot and Morgan 1981, pp. 143–6).[4] The Energy Commission has been responsible for a considerable amount of technology-push activity in solar energy technologies over the years.[5] Particular programs of note have included the Energy Technologies Advancement Program (ETAP), enacted in 1985 as a result of the Rosenthal-Naylor Act of 1984, and the later Public Interest Energy Research Program (PIER) (Hollon 1980, pp. 8–9).[6] PIER was established in 1998 as a result of electricity restructuring, to help replace utility R&D funding (ibid.).[7]

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[4] The act gave the state the responsibility for reliable power that did not deplete natural resources or threaten environmental quality. According to Sawin (2001, p. 166), "utilities strongly opposed the Act and Governor Reagan vetoed it early on. But a heightening of the oil crisis" ultimately led Reagan to pass it.

[5] The property tax reductions accompanying Proposition 13 in June 1978 seriously curtailed the funding levels of the Energy Commission, and "resulted in a suspension of funds for the state's renewable energy program" (Sawin 2001, p. 171).

[6] The Energy Research, Development, Demonstration, and Commercialization Act of 1993 (SB 789) extended the operation of the Rosenthal-Naylor act through 2004. The repayment period of 90 months in the Rosenthal-Naylor act was extended to 20 years via SB 1922, which also established small business loans for alternative energy. (Sawin 2001, pp. 196–7).

[7] The California Public Utilities Commission (CPUC) traditionally monitored utility R&D, particularly with respect to clean energy technologies. As a result of this process, the California utilities led the industry with respect to renewable energy, including solar technologies. Indeed, "through the 1970s, utilities in California were the only ones involved in renewable energy technologies; no private producers were in the picture yet" (Sawin 2001, p. 171). The restructuring of the electricity sector has resulted in reduced ratepayer funded R&D, as utilities have less flexibility and incentive to invest in this activity. R&D in advanced generation technologies in California dropped 85% between 1993 and 1995, while

Within the Energy Commission, the Solar Office (inside the Research and Development Division), had several important functions in the 1970s. Besides drafting and technically supporting solar legislation, administering federal and state grants and contracts for solar commercialization, and providing technical assistance to a variety of solar stakeholders, it also ran two major projects. First, starting in 1978, it operated the Testing and Inspection Program for Solar Equipment (TIPSE), which certified solar collectors for performance and durability. Second, following in the footsteps of the California city of Santa Clara, which in 1975 established the nation's first municipal solar utility (MSU) to supply, install, and maintain SWH systems for residents and local businesses, the Solar Office worked together with six California cities—Oceanside, Santa Monica, San Dimas, Bakersfield, Ukiah, and Palo Alto—to develop plans for further MSUs (Bereny 1977, p. 246; Hollon 1980, pp. 8–9).[8]

When Jerry Brown took over the California governor's office, also in 1975, the political climate for renewable energy policy became very favorable. Legislation that advanced solar energy technologies during his two administrations in the 1970s included:

- AB 2740 (1976), which authorized solar provisions in state building codes ;
- SB 150 (1977), which called for solar systems to be used in all new state buildings, where feasible;
- SB 373 (1978), which provided interest-free loans for solar energy systems to disaster victims engaged in rebuilding;
- AB 2225 (1978), which authorized banks and savings and loans to extend first mortgages and increase new home loans in order to finance solar systems;
- AB 2851 (1978), which increased Cal-Vet home loans by $5,000 to allow for the installation of solar systems;
- AB 3250 (1978), which allowed solar rights to be provided in local ordinances and private covenants; and
- AB 2321 (1978), which protected solar collectors from future shading (Berman and O'Connor 1996, p.30).[9]

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contributions from the state's investor-owned utilities to the electricity sector's R&D consortium, the Electric Power Research Institute, dropped 50% between 1994 and 1995 (Zucchet 1995, p. 36).

[8] Santa Clara primarily focused on SWH for swimming pools, maintaining the equipment and charging homeowners a fixed fee for the service. Each of the cities evolved with local circumstances to become more of an "energy utility," with programs ranging from leasing operations to energy information. The Energy Commission and these six cities formed a "joint powers authority"—the California Solar Energy and Conservation Development Authority (CalSECDA) —to help local governments work with MSUs. CalSECDA, which eventually included 14 local governments and community organizations, "provided its members with legal advice, education and training programs, and technical consultants." With the demise of the federal funds that financed the program, the Energy Commission eventually withdrew its support of CalSECDA, although some MSUs survive today (Coe 1985, pp. 204–06).

[9] The Solar Rights Act was amended in 2003 in AB 1407 (Wolk, Chapter 290, Statutes of 2003), which

In addition to this tangle of demand pull instruments, which can be categorized as standards, procurement policies, a variety of purchase subsidies, and solar access rights, the most famous California policy to promote solar energy in the 1970s was the generous residential tax credit for purchasing solar installations. Initially established in SB 218 (1976), it provided a state income tax credit of 10% of the cost (or $1,000, whichever is lower) of solar energy equipment for heating, cooling, and producing electricity, with an expiration date of December 31, 1980. The credit (with the same expiration date) was modified in AB 1558 (1977) as a 55% tax credit (or $3,000 for each new system), net of federal credits (Quigley 1991, p. 325). This meant that claimants had to subtract the federal rebate of 40% out "so in most cases, the real state-tax rebate came out to 15% of the value of the solar installation" (Hollon 1980, p. 22). In this bill, both single and multi-family dwellings were eligible for the credit, as were conservation measures installed in conjunction with a solar system; for multi-family dwellings, the 55% credit applied to systems costing less than $12,000. In AB 3623 [author ?, Chapter 1159, Statutes of 1978], the 55% credit (same expiration date) was expanded to include the cost of acquiring a solar easement. In addition, the builder of a new single-family dwelling could claim a 25% credit or pass it on to original buyer (Hollon 1980, pp. 12, 14). Finally, in SB 995 (1979), the solar tax credit was extended to solar energy systems leased from municipal utilities.

In support of the solar tax credit, the Energy Commission and the California Solar Energy Industries Association (CAL SEIA) ran the CAL SEAL program, beginning in 1979. This program put the CAL SEAL label on solar installations that were determined by CAL SEIA to meet the technical requirements necessary to receive the tax credit (Sawin 2001, p. 178). Note that solar installers did not have to pass stringent licensing requirements. As administered through the Solar and Insulation Unit of the Department of Consumer Affairs (established in 1978), six classifications of licensed contractors could receive the supplemental solar license by simply filling out a form and paying $35, with no experience or testing required (ibid. p. 17).[10]

Two other important California actions occurred in the 1970s, one institutional and the other using the electricity regulatory structure to drive the development of renewable energy. In the first action, the Office of Appropriate Technology (OAT) was established within the Governor's Office of Planning and Research in 1976, in order to help develop "small scale, decentralized technologies that rely on renewable energy sources" (Talbot and Morgan 1981, p. 82).[11] In the establishment of OAT, the state was entering on one side of a debate in solar advocacy circles about the federal R&D establishment's focus on "Big Solar" projects, like Power Towers and Solar Power Satellite Systems, rather than on Amory Lovins' "soft path" smaller-scale solar technologies.[12] It also ran a solar job-

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extended solar rights to "cities, counties, municipalities, [and] other public entities" (IREC 2006). AB 2473 (Wolk, Chapter 789, Statutes of 2004) further expanded the act in 2004 (ibid.).

[10] Today, the Solar Specialty license (C-46), issued by the California Contractors State License Board, requires four years' experience, trade exams, and law exams (IREC 2006).

[11] The office terminated June 30, 1984 (Sawin 2001, p. 467).

[12] See Reece (1979).

training program used for employees of the federal employment and training program CETA (Comprehensive Employment and Training Act).

In the second action, the CPUC Code Section 454 provided a “carrot” for renewable energy generation by allowing utilities to get a “higher rate of return on their investments (of 0.5–1%) if they invested in projects designed to generate” energy from renewable technologies that was cheaper than power from conventional technologies (ibid., pp. 81–2, 87). The CPUC also provided a repeated “stick” to drive renewable generation, by repeatedly warning California utilities that “they would be penalized for failing to aggressively pursue cost-effective renewable energy strategies” (EIA 2005). In 1979, the CPUC withheld part of a rate increase from Pacific Gas & Electric (PG&E) and came close to fining Southern California Edison (SCE) because it considered them derelict in adopting cogeneration strategies (Watanabe 1995).[13] “Within months, PG&E had lined up several major cogeneration contracts. Southern California Edison, meanwhile, announced a massive renewable energy initiative designed to meet 30% of the company’s new energy needs by 1990” (ibid., p. 87).

International: A number of countries, including Japan, Germany, and the Netherlands, began solar R&D programs in the 1970s, at least partially in response to the oil shocks of 1973 and 1979 (IEA 2006).

The primarily technology-push “Sunshine Project” in Japan in 1974 is the most significant of these. Its goal was to develop clean energy technologies, including clean coal technologies (primarily coal liquefaction and gasification), hydrogen energy, and solar technologies with a very big “S,” including STE, PV, geothermal, wind, ocean, and biomass (Watanabe 1995, p. 243). Figure 3 shows R&D budgets for solar technologies in Japan, as separated out by specific application. Note that in the 1970s, solar thermal technologies received the bulk of R&D resources, although Japan is today most famous for its development of PV.[14]

[13] In 1983 the CPUC fined SCE $8 million for not adequately accelerating its development of renewables (Sawin 2001, p. 465).

[14] The Dutch program similarly focused on solar thermal in the 1970s, with a later shift to PV (EIA 2005, p. 19).

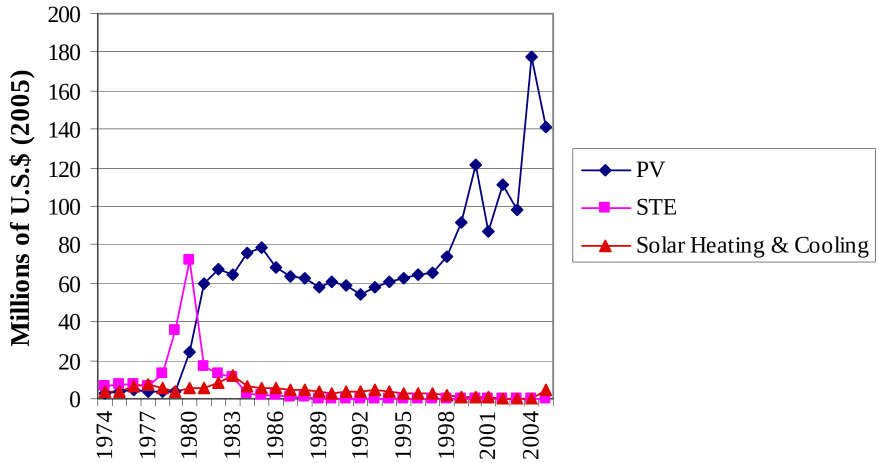

Figure 3. Solar R&D in Japan

Source: (Watanabe 1995)

In 1978, Japan initiated another R&D program—the Moonlight Project—to develop energy conservation technology. The Japanese Ministry of International Trade and Industry (MITI) administered the Sunshine and Moonlight Project budgets, as well as other energy R&D (e.g., coal, oil, natural gas, nuclear, electric power), at percentage levels shown in Figure 4. Note that the Japanese government's belief that the government's "R&D budget is best utilized when it induces the industry's broad R&D activities" has meant that, in general, the ratio of government support to total R&D expenditures is only 3%, and that has held true in the manufacturing sector, which performs the majority of energy R&D in Japan (Stoft 2006).

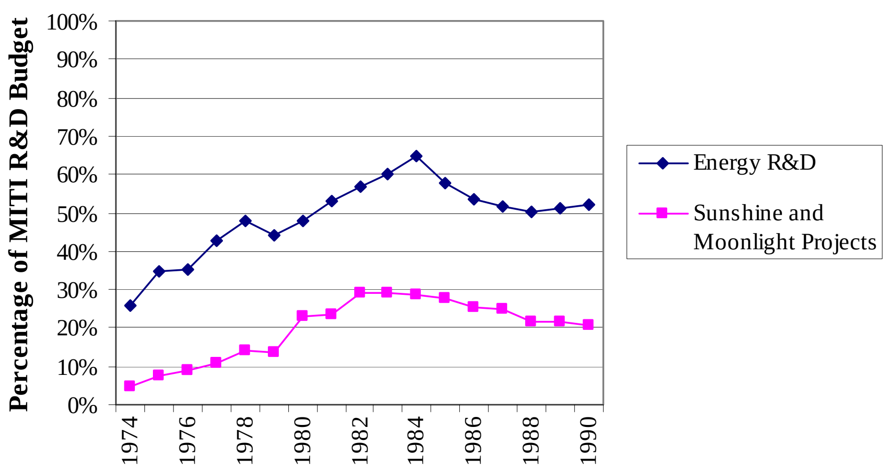

Figure 4. Percentage of MITI R&D budgets devoted to sunshine and moonlight projects, as well as energy overall

Source: (Larson and West 1996, p. 103)

1.2.3. 1980s

Federal: Much of what was built in the 1970s, regarding institutional and legislative support of solar energy technologies, declined in the 1980s. Two major causes of this were the anti-energy policy Reagan administration in 1981–1988 and declining oil prices through much of the decade (see Figure 5 for the trend in gasoline prices from 1970 to 2006).

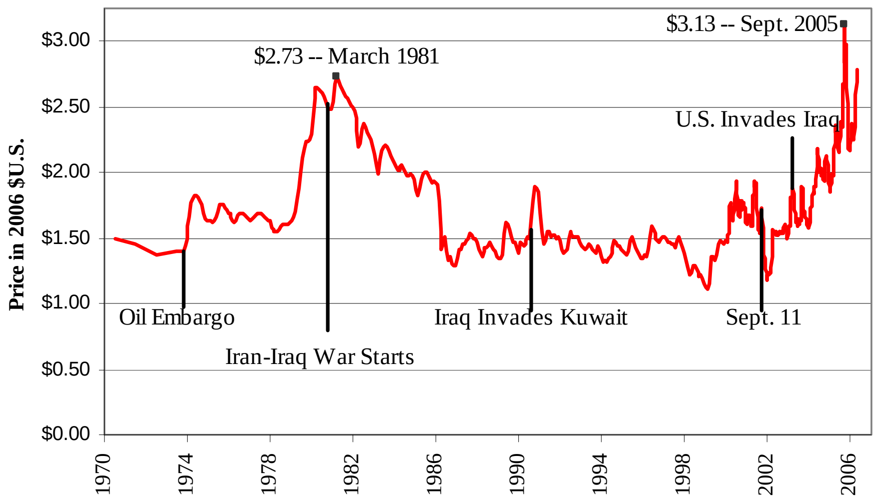

Figure 5. Regular gasoline prices, 1970–2006, in 2006 U.S. dollars

Source: (Margolis 2002, p. 75)

The decade started off with two minor legislative successes for solar, however. The Crude Oil Windfall Profits Tax Act of 1980, P.L. 96-223, increased the ETA's residential tax credit to 40% of the first $10,000 of an installation (up to a $4,000 maximum) retroactively to January 1, 1980, and expanded eligible equipment to include electricity generation. It also increased the business tax credit to 15%, leaving the expiration date for both residential and business tax credits at December 31, 1985 (Larson and West 1996, p. 104). Finally, it extended the residential tax credit to PV (the business tax credit already applied to PV systems) (Hempel 1983, p. 205)

Meanwhile, the Energy Security Act of 1980, otherwise known as the "Synfuels" Bill, P.L. 96-294, was transformed from Carter's original intention of solely promoting a Synfuels industry to become more of "an omnibus energy bill, approaching the National Energy Act in scope" (Hempel 1983, p. 206). Title IV, the Renewable Resource Initiative, and Title V, the Solar/Conservation Bank, were relevant to solar energy. Title IV had several provisions promoting solar energy and conservation, as it:

> "(1) required DOE to coordinate its solar and conservation outreach activities and report annually to the Congress; (2) created a three-year pilot program within DOE to demonstrate energy self-sufficiency in one or more states through the use of renewable resources; (3) clarified the eligibility of federal facilities which could participate in the Federal Photovoltaic Utilization Act [§§ 561–569 of title V of the ETA were cited

> as such]; and (4) relaxed the rules for qualifying facilities under PURPA" (ibid.)

Title V established the Solar Bank described in Carter's June 20, 1979, solar address described in the 1970s section above. It was scheduled to open in the spring of 1981 with $125 million to cover its first year, but politics intervened (Sklar 1990, p. 128).

Ronald Reagan entered office in 1981, having campaigned, in part, on a promise to close the DOE and "build production of conventional fuels and nuclear power" (ibid., p. 197). In March, 1981, Reagan announced that he was planning to eliminate the Solar Bank, but by the end of the year, Congress had appropriated $23 million in order to begin its operations immediately. Then

> "the Reagan administration responded with what amounted to an impoundment of the Bank's appropriation, thereby inviting a suit to force the release of approved funds. Such a suit, charging the Regan administration with violating the Impoundment Control Act of 1974, was filed in the spring of 1982 by five Congressmen, the cities of Philadelphia and St. Paul, and a number of pro-solar and environmental organizations" (Sklar 1990, p. 205)

The suit was eventually won by the Bank's supporters, and the Bank operated under the Department of Housing and Urban Development (HUD) until it was repealed as part of P.L. 102-550 in 1992.

The fight over the Bank was indicative of the kinds of fights that occurred during the Reagan administration over both supply push (R&D) and demand pull (tax credits) for solar energy. On the supply-push side, Reagan officials repeatedly proposed drastic budget cuts in solar energy R&D programs and Congress regularly appropriated higher amounts than administration requests. Nevertheless, dramatic cuts occurred in R&D funding in the 1980s, as shown in Figure 1.

On the demand-pull side, on September 24, 1981, Reagan announced in a national address that he was "proposing to trim $3 billion of tax giveaways from the Treasury, with the solar and conservation tax credits being among the prime targets" (Sklar 1990; Gielecki, Mayes et al. 2001; Margolis 2002). Although the proposal was put aside in the face of strong bipartisan opposition in Congress, the threat alone did severe damage to the solar industry, scaring off potential customers and "driving many marginal firms into other lines of business" (ibid., p. 207). The residential solar tax credit ultimately survived to its original expiration date; that expiration was credited with causing the closure of 200 companies and the loss of at least 35,000 jobs (Gielecki, Mayes et al. 2001). The business solar tax credit for both PV and solar thermal technologies fared better. It was renewed retroactively from January 1, 1986, through December 31, 1988 at the 15% level in 1986, 12% level in 1987, and 10% level in 1988 as part of the Tax Reform Act of 1986, P.L. 99-514, then extended annually until 1992 (IREC 2006).

The new legislation that did pass in support of solar energy technologies in the 1980s was relatively minor. In 1981, the Economic Recovery Tax Act (ERTA), P.L.97-34, instituted the Accelerated Cost Recovery System (ACRS), whereby most solar energy technology investments—not owned by utilities—were allowed to depreciate over five years, rather than the normal fifteen (Moomaw, Serchuk et al. 1999, p. 77).[15] Note that in 1982, the Tax Equity and Fiscal Responsibility Act (TEFRA), P.L.97-248, "canceled further accelerations in ACRS mandated by ERTA" (Moomaw, Serchuk et al. 1999). In 1986, the Modified Accelerated Cost-Recovery System (MACRS) was established at 26 USC § 168 (2005), and it continues in force today. Under MACRS, the solar "class life" for property depreciation deductions is five years (Lotker 1991, p. 18).[16]

In addition, two pieces of legislation occurred in the 1980s that modified the 30 MW size restrictions that allowed QFs under PURPA to be protected from regulation as utilities. Although these legislative actions did not affect many U.S. companies, they made a big difference to the company that lobbied for them, Luz, the only company in the U.S. to commercialize STE. (Created in 1979, Luz had constructed nine "Solar Electric Generating System" (SEGS) plants in California, generating 95% of the world's solar generated electricity, by the time it declared bankruptcy in 1991 (Sawin 2001, p. 185).) In the first legislation, passed in 1987, the size limit was lifted to 80 MW for a two year moratorium, "during which current and future plants could be grandfathered under the law" (Quigley 1991, pp. 325–7). The moratorium window expired at the end of 1989. In 1990, the second legislation, the Solar, Wind, Waste, and Geothermal Power Production Incentives Act of 1990, P.L. 101-575,

> "removed the MW limits completely so long as the plant was certified as a QF before the end of 1994 and actually constructed before the end of 1989. This allowed Luz to begin to design larger plants and allow for operation of the existing 80 MW SEGS VIII and IX at levels above 80 MW" (Quigley 1991)

Unfortunately, "the manner in which the limits were implemented and removed caused a number of difficulties" for the company. Even at the new limit of 80 MW,

> "Luz was constrained from designing a plant sized at an optimal level (which would have had a capacity even greater than 80 MW). The limit was unfair in that, by the late 1980s, avoided capacity and energy costs were being established by conventional utility or cogeneration plants which had no such limits. [and] Even in removing the limit altogether, the sunset provision imposed by the legislation resulted in a crucial uncertainty in Luz's future. Any long term investor considering supporting Luz would have to carefully examine the likelihood that after

[15] ERTA also contained the initial R&D tax credit, intended to give U.S. firms a temporary incentive to increase their spending on R&D and thus spur long-term economic growth (Margolis 2002, p. 87).

[16] California also dealt with this issue in the 1980s. In 1980, AB 2893 "allowed for straight line amortization of pollution control equipment or alternative energy equipment" with "the amortizable basis … reduced by the amount of any public grant" (Sawin 2001, p. 184). It also defined pollution control equipment as including "'solar energy' ... placed in service by year-end 1985" (Sawin 2001). In 1982, AB 3788 "allowed for a depreciation deduction over a 60 month period for property used in a trade or business (or held for production of income) for taxable years beginning prior to 1 January 1987."

> the sunset dates of 1994 and 1999 … new solar electric QFs … would once again be limited to 30 MW” (Quigley 1991, p. 19)

California: As in the United States as a whole, the 1980s saw a decline in California in government actions to support solar energy. Also as in the United States as a whole, the 1980s in California were dominated by a Republican chief executive who worked to end tax credits in support of solar energy. But both the decline in government actions and the Republican chief executive came later in California than in the United States overall. Indeed, the opening years of the 1980s saw both policy innovation and exercise of state authority on federal policies that continued to support solar energy. Note that many of the policy instruments instituted in California in the 1970s and 1980s “continue to exist but have been dormant for years.” (Quigley 1991, p. 295)

The tax code was the setting for a number of California innovations in solar energy policy. As stated in the California section in the 1970s, the state had a famous income tax credit for solar energy that went through periodic revisions, beginning in 1976. The solar tax credit continued until December 31, 1986, with periodic bouts of uncertainty on their extension, levels, and eligibility requirements. Table 2 summarizes the major changes that occurred to the state’s solar tax credits in the 1980s.

Table 2. California state income tax credits for residential solar applications in the 1980s

Year	Bill	Credit	Eligibility/Limitations	Expired
1980	AB 2036	55% up to $3,000 net of federal credits	Extended and expanded existing credit to include all residential applications; reduced credits for recreational or therapeutic SWH systems to 25% in 1983	12/31/83
1983	State budget	50% for solar systems up to $3,000 net of federal credits	Eliminated all credits for solar heating of swimming pools and spas. Required carryover of some credits.	12/31/86
1983	SB 298		Lowered credit for builders of single-family dwellings who claim credits (instead of passing them on) for systems eligible for federal tax credits to 15%; expanded eligibility of leased solar systems	
1985	SB 125, SB 1079	Basis shifted from net to gross of federal credit	Broke link between federal/state credits; prohibited certain carryovers	
		10% single family; 25% multifamily up to $1,000		12/31/86

Source: (Quigley 1991, p. 332)

At the beginning of the decade, the state's solar tax credit was set at 55% (or $3,000 for each new system), net of federal credits, and there was considerable uncertainty over whether the credit would be renewed past its original expiration date of December 31, 1980. AB 2036 extended the tax credit to December 31, 1983, as well as expanded it to cover all residences (it had formerly applied only to single-family homes). As Table 3 points out, the most popular investment beneficiary of the solar tax credit up to and including 1980 was swimming pools and hot tubs. This was politically sensitive, so one of the provisions of AB 2036 established "successive reductions in the credits available for recreational or therapeutic solar energy water heating systems, from 55% in 1980 to 45% in 1981, to 35% in 1982, and to 25% in 1983" (Quigley 1991, p. 295).

Table 3. Solar investments qualifying for California tax credits, by type (selected years)

	1978	1979	1980	1981	1982	1983
A. Number of claims (thousands)						
Pool, spa	10.9	32.9	60.6	16.9	8.5	4.2
SWH	1.7	4.4	17.3	30.9	28.3	36.2
Heating/air conditioning	2.3	1.0	2.8	3.1	4.0	6.5
Multi-family/Solar	1.9	1.8	4.3	10.0	8.3	4.0
Total	*16.8*	*40.1*	*85*	*60.9*	*49.1*	*50.9*
B. Qualifying Investments (value in $ millions, distribution by percentage)						
Pool, spa	16.2 (51.4%)	46.2 (58.0%)	92.8 (48.5%)	48.4 (21.2%)	18.5 (8.1%)	8.0 (2.7%)
SWH	6.2 (19.7%)	17.5 (22.0%)	60.1 (31.4%)	117.0 (51.2%)	110.1 (48.2%)	192.2 (64.2%)
Heating/air conditioning	3.9 (12.4%)	5.4 (6.8%)	14.6 (7.6%)	6.6 (2.9%)	47.4 (20.8%)	71.3 (23.8%)
Multi-family/Solar	5.2 (16.5%)	10.5 (13.2%)	23.7 (12.4%)	56.5 (24.7%)	52.3 (22.9%)	28.1 (9.4%)
Total	*31.5*	*79.6*	*191.2*	*228.5*	*228.3*	*299.6*

Source: (Quigley 1991, p. 296)[17]

In 1983, California inaugurated a new governor, George Deukmejian, who had made a campaign promise to end the state's solar and energy conservation tax credits. In response to the new governor's proposal, the legislature amended the state budget to extend the credits through December 31, 1986. The budget was also amended to reduce the solar tax credit to 50% and eliminate the credit for swimming pools and hot tubs by August, 1983 (Kinnee 2005). Also in 1983, SB 298 made two revisions to the residential tax credit. First, it reduced—from 25% to 15%—the tax credit for builders of single-

[17] Solar investments by household income class are also detailed in this source.

family homes who claimed credits (instead of passing them on) for systems eligible for federal tax credits. Second, it expanded the eligibility of leased solar systems for the tax credit (an important provision for MSUs). Regarding non-residential properties, it expanded the 25% tax credit for solar installations to all installations, rather than just those costing $12,000 or more (ibid., pp. 295–6).[18]

Despite these changes, the solar tax credit remained in some political jeopardy, particularly with tight state budgets, Deukmejian's disfavor, and the expiration at the end of 1985 of the federal tax credits. In 1985, California enacted SB 125 and SB 1079, which:

1. "deleted provisions that link[ed] state tax credits to eligibility for federal credits";
2. limited the single-family residential credit to "10% of the system cost, regardless of the availability of [the] federal credit, up to a maximum credit of $1,000";
3. limited the multi-family residential credit to "5% of the total cost, with no maximum credit per unit"; and
4. limited the commercial/industrial credit to "25% of the total system costs" (Sawin 2001, p. 185).

Even with these changes, there was no extension of the solar tax credit after 1986.

In addition to the direct tax credit for solar energy technologies, the voters of California passed a ballot proposition in 1980 to amend the state's constitution and give the legislature the authority to exclude the construction of solar energy systems from property tax. Proposition 7 was implemented in Section 73 of the Revenue and Taxation Code and made operational for the fiscal years 1981–82 through 1990–91, thanks to SB 1306 (Alquist, Chapter 1245, Statutes of 1980) and AB 1412 (Wyman, Chapter 878, Statutes of 1985). A further extension through the 1993–94 fiscal year was vetoed by Deukmejian, but in 1991, SB 103 (Morgan, Chapter 28, Statutes of 1991) extended it for 1991–92 through 1993–94, when Deukmejian was no longer in office. The property tax exclusion expired on January 1, 1995, but was reinstated in AB 1755 (Keeley, Chapter 855, Statutes of 1998) for the fiscal years 1999–2000 through 2004–05 (Coe 1985, p. 199). AB 1099 (Negrete-McLeod, Chapter 636, Statutes 2003) extended it further, through December 31, 2009 (IREC 2006).

Besides this series of tax actions, the California legislature engaged in other actions on behalf of solar energy. In 1980, California began to issue bonds "to finance the acquisition, construction, and installation of facilities using alternative energy technologies or sources for electricity generation"(Galloway 2000, p. 28).[19] Also in 1980, the legislature appropriated $2.5 million to start the California Business and Industrial

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[18] SB 298 also "extends from 36–60 months the period over which a depreciation deduction for the cost of a solar energy system may be allowed" (Sawin 2001, p. 193).

[19] In 1994, SB 215 increased the limit on financing assistance from $200 million to $350 million (Sawin 2001, p. 185).

Development Corporation, which was designed to support alternative energy businesses (ibid.).

In 1982, the legislature appropriated $750,000 to start and operate the State Assistance Fund for Energy-California Business and Industrial Development Corporation (SAFE-BIDCO). This state-owned nonprofit, still in existence today, provides loans to small businesses in "any technology or technique which displaces conventional fuels and nuclear energy" (EIA 2005). As of 2000, SAFE-BIDCO made five-year loans at 5% to small businesses for energy efficiency and renewable energy projects. There are two main criticisms of SAFE-BIDCO, from the viewpoint of spreading the diffusion of distributed solar applications: (1) "most solar energy systems cannot meet this short payback period"; and (2) industry representatives, other than the program administrators, claim that "most businesses in the state are not aware of the program" (Berman and O'Connor 1996, p. 37).

Legislative action on behalf of solar energy was not the only type of government action in play during the 1980s in California. The CPUC, in particular, was a prominent and innovative actor in support of solar energy technologies. In its role as a state agency implementing PURPA, the CPUC played a vital role in laying the financial groundwork underpinning the solar industry for many years. It also passed relatively short-term, creative measures that worked to support the industry.

As explained in the 1970s section on California, above, PURPA mandated that utilities: (1) pay for power from QFs at "avoided costs," or the costs saved by not having to build new power plants, and (2) sell back-up power to QFs at non-discriminatory rates. California, like all the states, was given discretion over the implementation of PURPA, and used its discretion to make PURPA a stronger demand-pull signal than in many other states.

In 1982, the CPUC rewarded state QFs with high avoided costs that reflected expectations in the early 1980s of high future prices for natural gas and oil. After the first ten years at the high rate set in this decision, the purchase price for QF power was automatically to revert to the actual avoided cost.[20] As this cost turned out to be much lower than had been initially predicted because oil prices had dropped considerably during the 1980s (see Figure 5 for a representative price trend), the price that QFs received after those first ten years dropped dramatically. This drop-off is sometimes referred to as the "11–year cliff" (EIA 2005, p. 10). It was actually worse for solar energy producers than wind energy producers; by 1992, California utilities paid about "6 cents per kWh for wind [power], but only … 3-4 cents per kWh for excess household PV energy" (Sawin 2001, p. 463).

[20] In at least one case, however, the avoided cost quotation appears to have changed before those ten years had concluded. According to a "project manager for several cogeneration plants in Northern California" interviewed in (Berman and O'Connor 1996), "in 1985, the price PG&E paid was 7.2 cents per kWh. But in 1987, after PG&E claimed the rate was too high, the CPUC allowed it to drop its payment to 3.05 cents per kWh."

Also in 1982, the CPUC created ten-year power purchase agreements at a price of 6–9¢/kWh in Decision 82-01-103.[21] These Standard Offer Contracts, numbers 1–3, "were based on the notion that there should be no difference in electricity rates regardless of whether the electricity was generated by a utility or by a QF" (Guey-Lee 1999). In 1983, the CPUC followed these contracts with interim Standard Offer Number 4 (ISO4) contracts (CPUC Decision 83-09-054). These contracts used long-term avoided costs as the price basis for long-term guarantees (a 15–30 year contract with the first 10 years at a guaranteed price) of payments based on energy produced and capacity installed (Sawin 2001, p. 172). An EIA analysis calculated that these contracts guaranteed an effective tariff of 12¢/kWh (Sawin 2001, pp. 470, 480, 176). The CPUC withdrew the ISO4 contracts in 1985 "due to concerns of excess capacity and overpayments" (ibid., 172, 176, also see Rader and Bossong 1990, pp. 51–2).

As the name states, the ISO4 contracts were designed to be "interim" until Final Standard Offer Number 4 (FSO4) contracts could be implemented. Although the structure for the FSO4 contracts was first approved by the CPUC in 1986, the final decision on them was not issued until 1992, and even then, the FSO4 contracts were ill-fated; they were never implemented due to the fallout from a FERC decision on California's approach to advancing renewables within the framework of utility restructuring (Coe 1985, p. 202). The Standard Offer Number 2 contracts were suspended in 1986 when the world oil market crashed, while Standard Offer Numbers 1 and 3, "neither of which readily applied to renewable energy technologies," ended with restructuring in 1996 (Hollon 1980, p. 70).

As a state agency with authorization over the state's investor-owned utilities (IOUs), the CPUC found other innovative ways to support solar energy development in California. In 1978, San Diego Gas and Electric (SDG&E) began financing and installing fifty SWH systems on rooftops in its service area. The CPUC stopped the program out of concern over whether utilities should behave like banks. Upon consideration, the CPUC itself began to explore utility financing programs for SWH in a proposal that included such options as utility ownership of systems, with ratepayer payment of costs, and utility low-interest loans to SWH system buyers. Criticisms of this proposal—on the basis that it "elbowed out the private sector" by either making utilities into banks or allowing them to monopolize supply of SWH systems—resulted in the establishment of the Solar Energy and Conservation Mortgage Corporation (Sunny Mac) in 1983 (Coe 1985, p. 207). In 1980, however, the proposal itself evolved into a three-year "Demonstration Project" by the CPUC in which the state's investor-owned utilities—PG&E, SCE, Southern California Gas (SoCal Gas), and SDG&E—were required to provide a choice of 6%

[21] These contracts were designed to address the delays private developers faced in negotiating purchase contracts with the utilities, which were "reluctant to agree to such contracts because of concerns about viability of projects, and concern that CPUC might not consider the contracts reasonable" (Sawin 2001, p. 173). They were also designed to address concerns about possible under-supply, given long construction delays in the states nuclear plants (ibid).

interest loans or rebates for SWH systems (ibid., p. 209, Hollon 1980, p. 70).[22] While both programs were innovative, neither is considered a real success today.

Sunny Mac was the less successful of the two programs, as it never officially opened its doors. A joint project of the savings and loan (S&L) industry and the solar industry, it was established with seed money from California in 1983 in order to provide a secondary lending market for SWH loans. Modeled after the federal mortgage secondary market corporations, its business model was to sell shares to participating lenders, who would then be able to sell their loans to Sunny Mac for slightly less interest than they charged them out. It needed to sell $3 million in shares in 1983 in order to get started; by October of that year it was clear that the goal was impossible to meet that year, and ultimately, the seed money had to be repaid to California. Observers at the time attributed Sunny Mac's demise to management inadequacies and bad timing. The timing was particularly poor: the nation was in a recession, deregulation had resulted in major restructuring and instability in the S&L industry, and the solar industry was suffering uncertainty due both to Reagan and Deukmejian administration policies.

The timing was also close on the heels of the end of the Demonstration Project, which was catalyzed by the CPUC president Leonard Grimes in an effort to provide utility customers with "an independent means of lowering their bills" (Hollon 1980, p. 71). This project, not a traditional demonstration project but a demonstration whether "a new energy source could be made available through the existing … energy supply system," had the goal of retrofitting up to 375,000 residences with SWH, although only about 160,000 systems were installed by the end of the program in late summer of 1983 (Hollon 1980, pp. 30–33).[23] There were no restrictions on which installers could be used for the SWH systems, although the systems themselves were required to have five-year warranties. The utilities were also required to: (1) run inspection programs to check that installed systems operated properly, (2) educate the public about SWH, and (3) purchase and be responsible for installing 2,000 units for eligible low-income customers (Hollon 1980, p. 31).

In a Master's thesis in 1980, Jennifer Hollon interviewed thirty public and private-sector solar technology stakeholders on both the potential for widespread commercialization of SWH in California and their recommendations for how California policies and projects should proceed in this area. Even without the issuance of the final details of the Demonstration Project, Hollon could say that the project was unpopular with 29 of her 30 respondents, with the exception of one interviewee representing the CPUC. Several objections were raised, including: (1) a belief that solar systems should be distributed and independent of large utility companies; (2) a concern that it is inefficient for utilities to mimic financial institutions; (3) a concern that demand would not materialize as anticipated, yet the costs to ratepayers would be incurred, regardless of this fact; (4) a concern (among non-solar industry interviewees) that the solar industry could not meet the targeted demand; (5) a concern that the CPUC's cost-effectiveness equations were

[22] SDG&E was exempted from the loan option because of poor financial health.

[23] The multi-family residence part of the project was extended for a year through legislation, "to help make up for the delays in program start-up" (Coe 1985, p. 209).

inadequate (later upheld); and (6) a concern that the project would negatively impact the establishment of MSUs (Coe 1985, p. 209).

One of the more prescient objections was:

> "the fear that national publicity associated with the project might entice 'solar profiteers' to come to California. They added that absence of an established quality control mechanism could compound negative aspects of such an influx, resulting in an overall detrimental effect" (Coe 1985, p. 208)[24]

Hollon provides an insightful discussion of the likelihood of this occurring (ibid., pp. 45–6), given the inadequacy of solar licensing requirements at the time (see California policy in the 1970s section above). In this discussion, she predicted accurately that "the horror stories about improper installation that have been quietly circulating around the state," which all of her interviewees were aware of, would become widely publicized if a boom occurred in SWH installations. She also pointed out that the difficulties involved in assuring high-quality installations were one of the major problems facing localities that mandated SWH systems.

Considerable media attention accompanied the September 1980 announcement of the launching of the Demonstration Project, and various rebate quotas were quickly met.[25] As Hollon predicted, "the rebate program generated abusive sales and marketing techniques" including what the CPUC considered excessively high bids and "lifetime warranty" sales gimmicks in which the "lifetime" was for the company, not the SWH system (Galloway 2000). Note that the CPUC later placed a cap of $4,000 on the cost of each installation in response to early warnings about extremely high bids.

According to an assessment of the program written by Gigi Coe in 1985, the biggest problem from the tremendous interest in the program turned out not to be one of Hollon's predicted problems, but an inability on the CPUC's part to manage the program. Part of the problem was that the final details of the program were not resolved when the program was announced.[26] But the CPUC was criticized, in particular, as ill-suited (as a regulatory commission),

> "to making decisions with either speed or flexibility. Each program development or change was subject to a public comment period and full

[24] "Solar profiteers" were a phenomenon that her respondents already had experience with when previous local solar ordinances were established. "CALPIRG researchers found a 66 % turnover in solar businesses in San Diego Country from mid-1978 to mid-1979; Hartwell, Demeter, and other San Diego interviewees attributed part of this turnover rate to national publicity that stimulated an influx of good and bad solar businesses into the country.

[25] SCE's quota for single-family residents was met in three weeks, SDG&E's quota for natural gas customers was met in two months, and PG&E's quota was met by the beginning of 1981 (Coe 1985, p. 208).

[26] Such details included "freeze protection, details of the low interest loan terms, the CPUC's 'three bid' requirement, how the systems should be sized" and warranties (Coe 1985, p. 208).

> Commission review in a regulatory proceeding. In addition to adding to time and complexity, this also increased the cost for all parties involved who hired lawyers and filed endless briefs on the minutia of the rebate and loan scheme." (Coe 1985, pp. 209–10)

Besides stating that delays had plagued all elements of the program, Coe singled out three technical details of the Demonstration Project for particular criticism. First, she criticized the initial five-year full warranty and five-year limited warranty on parts as "an onerous requirement for any product, particularly one manufactured by a young, emerging industry," noting that the CPUC staff had initially proposed a ten-year warranty (ibid.). She also criticized the inspection requirements as complex and not reflective of "system designs then available on the market" (ibid.). Finally, she criticized the CPUC requirement of a "60% efficiency test based on water use per bedroom rather than per occupant," explaining that this forced out smaller, lower cost systems (ibid., p. 209).

Despite all the problems, the Demonstration Project did achieve an impressive level of diffusion of SWH technology in a short time. A 1984 CPUC evaluation of the Demonstration Project found that it was indeed well-subscribed by both single- and multi-family residences with natural gas backup heaters (88% and 84% of the target, respectively), although it was underutilized by single-family residences with electric backup (Galloway 2000, pp. 7–8). The multi-family program, in particular, "could be called a success" according to Coe, who also reported on Commissioner Grimes' opinions about the program:

> "He believes that the program savings and what was learned will far outweigh the miniscule cost to the ratepayers. However, he has also concluded that regulatory agencies such as the CPUC are not appropriate vehicles for instituting such programs, and that they are better done through the legislative process." (Sawin 2001, p. 190)

A 1987 CPUC report "concluded that continued subsidization of SWH systems was not cost-effective and did not serve the public interest" (Kurokawa and Ikki 2001).

One final action by a state agency should be noted in the 1980s. In 1988, the Energy Commission established the Energy Technology Export Program "to aid in the export of California energy technologies and services," including solar energy (EIA 2001; Margolis 2002; IEA 2006; OECD 2006). According to a survey conducted by the Energy Commission, "the ability to compete in the international market is considered essential for such firms to keep up with technological advances in the power plant business" (ibid.). Grant amounts to California-based companies were up to $50,000 in 1994, but by 2002 they had dropped to $25,000 (ibid.).

<u>International</u>: International government actions regarding solar energy in the 1980s were dominated by R&D programs, rather than demand-pull policies.[27] Figure 6 shows total

[27] Supply-push actions included organizational changes in R&D programs, rather than simple budget allocations. Japan, for example, passed the Law Concerning the Promotion of Development and Introduction of Petroleum Substituting Energy (LCPDIPSE) in 1980. This law "charged the government with adopting guidelines for the use of alternative energy sources and technologies and fiscal measures to

solar R&D expenditures by the United States, Japan, and Germany (in millions of 2005 U.S.$), as a proportion of each country's GDP (calculated by the expenditure approach and in millions of constant U.S.$ with constant exchange rates and an Organisation for Economic Co-operation and Development [OECD] base year). This proportional R&D measurement approach provides a comparative indicator concerning the overall effort a country invests in solar R&D. Note that while R&D efforts in the United States plummeted in the early 1980s, Japanese R&D efforts exhibited a gentler decline (Margolis 2002, p. 93). Indeed, starting in the mid-1980s, Japanese efforts, thus determined, exceeded those made by the United States for six years (1986–91).[28]

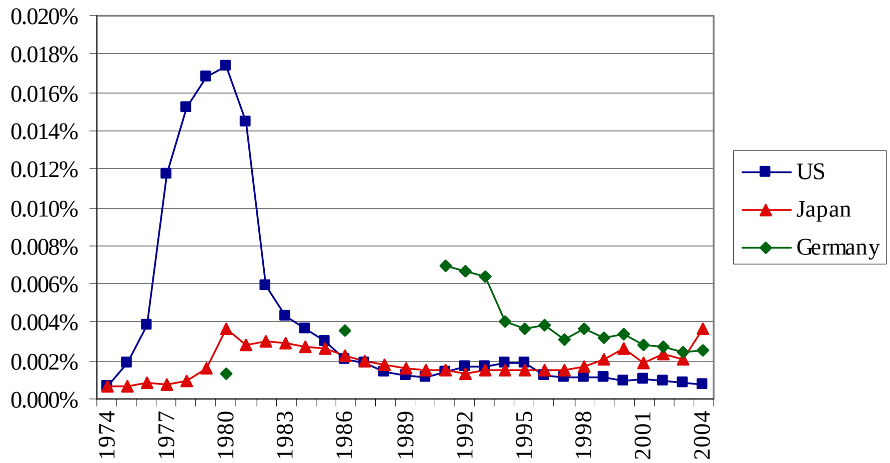

Figure 6. Total solar R&D as percentage of GDP in U.S., Japan, and Germany

Source: Adapted from data in (Margolis 2002, p. 89)

These Japanese efforts, as well as rapid production increases, paid off in terms of national share of the global PV market. At the beginning of the decade (1980), the United States dominated this market (76% of global production), with Japan in a distant second place (15%). By 1986, Japan was in first place (48%) with the United States in second (27%) (Margolis 2002).[29] As Margolis points out, the 1980s were a "time when the U.S. felt that it was losing its competitive edge in a host of industries, in particular with respect to Japan," and U.S. PV companies "like Cronar, Solarex and Energy Conversion Devices"

encourage their development" (EIA 2005). LCPDIPSE also created the New Energy Industrial Technology Development Organization (NEDO), a quasi-government agency founded in October 1980, funded by an electricity tax, and "staffed by both government and private sector employees on a 2–3 year rotating basis" (Margolis 2002, p. 91, Kurokawa and Ikki 2001). NEDO was established to promote non-petroleum energy development; among other functions, it works with MITI to coordinate solar R&D (especially PV).

[28] This situation occurred again, beginning in 1996, and continuing through 2004.

[29] Europe's share grew from 9% to 15% in this time period, with the rest of the world's share up to 9% by 1986.

were not exceptions to this trend (Margolis 2002, p. 93). In response to this threat, SERI launched its first cost-sharing project with industry, the Amorphous Silicon Research project, in 1984 (ibid.).

Even greater than the comparative decline of solar R&D in the United States as a percentage of GDP, as opposed to that percentage in Japan, is the comparative decline of the United States as opposed to Germany's R&D efforts in the 1980s (although these efforts did not lead to as threatening a market share position by Germany, as opposed to Japan, in the 1980s). Although consistent data for Germany is not available before 1991, data available in (Margolis 2002; IEA 2006) for PV alone points to Germany's efforts surpassing those of the United States and Japan beginning in 1986. Margolis further writes that the PV "program's budget grew fairly steadily from essentially zero in 1974, to … U.S.$ 58.0 million in 1992" (Margolis 2002). Figure 7 breaks down solar R&D in Germany by solar energy technology.

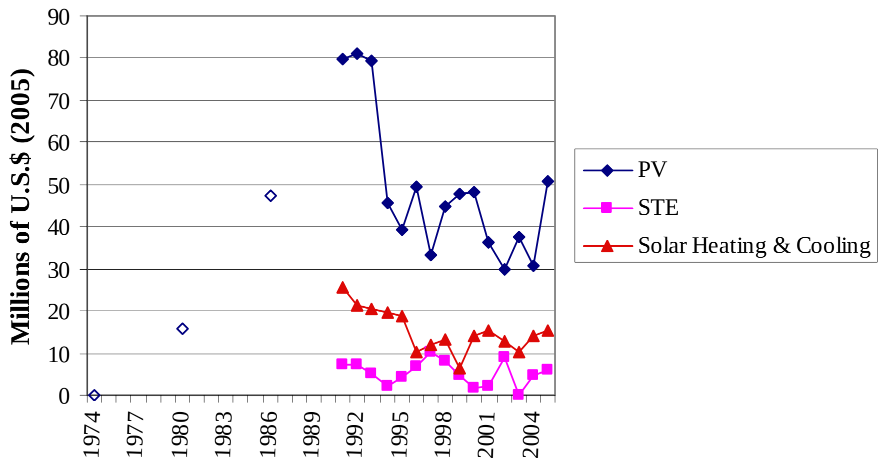

Figure 7. Solar R&D in Germany

Source: (SEPA 1991)

1.2.4. 1990s and 2000s

Federal:

The elder Bush administration and the Clinton administration were considerably more supportive of solar energy technologies than the Reagan administration, but oil prices remained low during these years and there was not much momentum for major policy efforts related to solar. A number of federal actions did occur, ranging from actions on the R&D side, such as renaming/reorienting SERI as the National Renewable Energy Laboratory (NREL) in 1991, to demand-pull related activities such as the establishment of production tax credits. Important government actions occurred during the years of the younger Bush administration as well, despite the fact that this administration was much less supportive of renewable resources than its two immediate predecessors.

One of the more significant federal actions that occurred in the 1990s and 2000s was the Energy Policy Act of 1992 (EPACT 1992), P.L. 102-486, which made the business solar tax credit permanent at 10% and established the Renewable Energy Production Incentive

(REPI) (Hester, Townsend et al. 1990; Moomaw, Serchuk et al. 1999). REPI provided annual payments of 1.5¢/kWh (based on 1993 U.S.$, indexed for inflation) for the first ten years of operation to eligible qualifying facilities. Eligible qualifying facilities had to use such energy sources as solar, wind, geothermal, biomass, and tidal, and had to be owned by such entities as nonprofits, public utilities, and state and tribal governments. REPI expired at the end of September 2003, although it was later reinstated, as discussed below.[30]

Also in 1992, a small group of utilities and industry organizations created the Utility Photovoltaic Group (UPVG).[31] In 1993, the UPVG proposed a cost-sharing partnership with DOE to accelerate PV commercialization for power applications. In 1994, this partnership, known as Technology Experience to Accelerate Markets in Utility Photovoltaics (TEAM-UP) began. TEAM-UP ultimately received $14.2 million in DOE funding, of which it used over $13 million to install 7.2 MW of grid-connected PV and the rest to fund off-grid applications. It leveraged these government monies with $60.3 million from industry. Through three rounds of funding between 1995 and 2000, TEAM-UP funded 35 ventures in 38 states, resulting in 1,162 individual PV installations (Hester, Townsend et al. 1990).

This public-private partnership was not the first in PV. In fact, it followed closely on the heels of Photovoltaics for Utility Scale Applications (PVUSA), which started in 1986 with funding from "a dozen electric utilities, the Electric Power Research Institute (EPRI), and Federal and State government agencies" and "two primary goals": (1) assessing the performance of promising PV technologies in various geographic areas, and (2) facilitating technology transfer between government, the utilities, and the solar industry (Peyton 2000). Although contracts for PVUSA test facilities were established in a number of states, including California, Hawaii, New York, and Virginia, California's test facility just north of Davis was arguably the most successful (IREC 2006). PG&E built the site and was its primary funder until 1996, when California electricity deregulation caused it to sell the site to the Energy Commission for $1. The Sacramento Municipal Utility District (SMUD) received a contract to manage the site, spent money "it believed would be reimbursed through federal grants," and lost that money "when the federal funding declined" (Sawin 2001, p. 421–22). Today, the city of Davis owns the facility and leases its operations to other companies. In 2002, SB 1038 (Sher, Chapter 515, Statutes of 2002) allowed Davis to purchase all of the site's power (about 800 kW in 2003) as well as treat that power "as a credit toward Davis' PG&E bill for city-owned and operated facilities" (Hayter and Martin 1998; Thomas, Hayter et al. 2000).

Perhaps as a result of the successes of PVUSA, in 1989 Congress passed the Renewable Energy and Energy Efficiency Technology Competitiveness Act, P.L. 101-218 (REEETCA), an act "to provide Federal assistance and leadership to a program of research, development, and demonstration of renewable energy and energy efficiency

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[30] Note that funds were "subject to the availability of annual appropriations in each Federal fiscal year of operation" (IREC 2006). Observers believe that this uncertainty limited REPI's effectiveness (Margolis 2002, p. 81).

[31] UPVG was renamed the Solar Electric Power Association (SEPA) in 2000.

technologies, and for other purposes." REEETCA placed a particular emphasis on joint ventures as an essential part of renewable energy R&D. It directed DOE to solicit joint venture proposals in PV, wind, solar thermal, factory-made housing, and advanced district cooling. At least one joint venture with at least one for-profit business was to be selected in each of these technologies, providing that at least 50% of the costs was provided by non-federal sources (Margolis 2002; NREL 2005).[32] In the case of PV, at least three cost-sharing PV programs of note occurred in the 1990s, including Building Opportunities in the United States for Photovoltaics (PV:BONUS and PV:BONUS2), the Photovoltaic Manufacturing Technology (PVMaT) project, and the Thin-Film PV partnership program. PV:BONUS occurred between 1993 and 1996 and PV:BONUS2 occurred between 1997 and 2001 (for more information, see Margolis [2002]). PVMaT began in 1990 and continues today (for more information, see Galloway [2000, p. 23]). The Thin-Film PV partnership program began in 1992 and is also ongoing (for more information, see Mingyuan [2005]).

These R&D cost-sharing actions signify a fairly active technology-push effort in solar energy technologies in the 1990s; demand-pull actions were considerably less strong, with one federal action in the middle of the decade having a particularly detrimental effect on solar markets. In 1995, the FERC made determinations on two cases—one involving Connecticut Light & Power Company and the other SCE and SDG&E—which considerably curtailed state pro-solar flexibility on the definition of the term "avoided costs" under PURPA. The importance of these FERC determinations in the California context will be explored in greater detail in the California section below.

Between 1995 and 2005, the only demand pull measures inducing solar at the federal level were relatively limited in scope. Although one of these actions had an ambitious title—the Million Solar Roofs Initiative (MSRI)—the resources underlying it have been rather limited. Established in June 1997 with the explicit goals of manufacturing and installing one million residential and commercial solar systems by 2010 and increasing the United States share of the market for PV, the MSRI is "wrapping up" in 2006 and appears to be well short of that goal. The basic idea behind the MSRI is that existing programs supporting solar energy technologies should be exploited more thoroughly.

> "Rather than buying systems or paying for the hardware, MSRI attempts to do three things. First, it works within existing federal structures to remove barriers. The program identifies all of the related federal government programs that already exist and tries to encourage loans from existing loan programs and get existing agencies to provide technical support and advice on how to overcome local barriers like building codes (Mulligan 2000). Second, the program allows groups that already exist to build alliances. It pulls together diverse groups like states, installers, and local solar NGOs. By committing to install over 500 systems, these groups can become MSR Partners and are eligible to receive some funding for their work towards this goal. [In 1999], 21 of the 40 partners received

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[32] Exceptions could be made in cases in which the joint venture was composed exclusively of small businesses or of a combination of small businesses and nonprofit entities, or if necessary to the successful operation of the proposed project.

> a total of about $500,000 to implement programs. An additional $200,000 in grant money was put towards national barrier removals such as a training on interconnection issues that was led by UPVG … And thirdly, MSRI keeps track of the number of solar installations that occur." (Mingyuan 2005; IREC 2006)

It is difficult to gauge the success of the MSRI, in part because it is very difficult to attribute a particular installation with a particular policy (i.e., the MSRI versus programs with more significant financial backing, such as TEAM-UP) (ibid.).

Another relatively modest demand-pull action in the late 1990s involved government procurement. Executive Order 13,123, which was issued by President Clinton in 1999, requires federal agencies to increase their use of renewable energy, including solar energy technologies installed after 1990, to a percentage to be determined later by the DOE. In 2000, the DOE set that percentage at 2.5% by 2005 (Sawin 2001, p. 177).

In 2002, another modest demand-pull federal action occurred, but this one returned to the financial incentives approach for supporting solar energy technologies that characterized parts of EPACT 1992 and earlier actions. The Renewable Energy Systems and Energy Efficiency Improvements program, passed in Section 9006 of the 2002 Farm Bill, requires the U.S. Department of Agriculture (USDA) to create a program to fund eligible agricultural producers and rural small businesses to purchase solar and other renewable energy systems, as well as increase energy efficiency. The program implemented by the USDA in conjunction with the DOE has gone from a basic grant program in fiscal year 2003 to a program that provides direct loans and loan guarantees, in addition to grants to entities with demonstrated financial need (Sawin 2001, pp. 174, 177). Rural Development grant funds may be used to pay up to 25% of the eligible project costs.

Thirteen years after EPACT 1992, the Energy Policy Act of 2005 (EPACT 2005), 42 USCS §13317, revisited broad-based financial incentives for solar and other renewable energy technologies. EPACT 2005 reauthorized REPI for fiscal years 2006 through 2026, as well as expanded the types of owners and technologies eligible for the incentive (REPI had expired at the end of September 2003) (IREC 2006). It also expanded the technologies eligible for the solar business tax credit, as well as temporarily increased the tax credit for solar technologies installed between January 1, 2006 and December 31, 2007 to 30% (after that date, the credit returns to 10%). EPACT 2005 also reintroduced the residential solar tax credit. In this iteration, a 30% tax credit (up to $2,000) is available for either or both PV and SWH systems installed on an individual residence between January 1, 2006 and December 31, 2007. To be eligible, SWH systems: (1) cannot be applied to swimming pools or hot tubs, (2) must be certified by the Solar Rating Certification Corporation (SRCC) or a comparable organization accepted by the state government with jurisdiction over the system, and (3) must draw on the sun for at least 50% of the energy used to heat the water used by the residence.

<u>California</u>:

Although California's commitment to solar energy technologies never really wavered, the instruments the state used to uphold that commitment changed significantly over the years, and particularly in the 1990s and 2000s, a period which saw energy policy dominated by electricity sector restructuring. Perhaps the beginning of the lengthy restructuring process in California occurred in 1987, when Stan Hulett, the CPUC Commissioner, began a proceeding to determine “why electric rates in California were 75%–80% above the national average” (Sawin 2001, p. 175). Although restructuring did not officially begin until the CPUC issued its *1994 Order Instituting Rulemaking* (known as the “Blue Book” for its cover’s color), the high electricity rates, including high payments to QFs, were an important element underlying the move to restructuring and earlier, more incremental changes to the Standard Offer contracts developed as part of the state’s response to PURPA (Sawin 2001, p. 179).

In 1989, the CPUC instituted the first Biennial Resource Plan Update (BRPU), which was intended, in part, to lead to the Final Standard Offer Number 4 (FSO4) contracts.[33] At the start of each BRPU, the three participating utilities—PG&E, SCE, and SDG&E—were to identify new generating capacity needs for the next twelve years.

> “The CPUC would then identify avoidable plants, and utilities were to respond by announcing the availability of long-run standard offer contracts based on the capacity, and fixed and variable costs, of the avoidable resource. Utilities had to bid to fill their capacity needs, with separate auctions for a required renewables portion.” (Sawin 2001, p. 176)

Both the CPUC and the state legislature, by their early actions in the 1990s, appeared to be interested in using markets to achieve energy policy goals, with some corrections to market prices for the non-market benefits of renewable electricity, such as resource diversity and environmental improvement. Besides the BRPU planning for renewables auctions, mentioned above, the legislature passed AB 3995 (Sher, Chapter 1475, Statutes of 1990), which required “the development of renewable energy sources and the inclusion of environmental costs and benefits in … future energy resource calculations” (Zucchet 1995, p. 37) In response, the Energy Commission and CPUC both issued values for air pollution from electricity generation and the CPUC further stating that these environmental externality values should be included both in QF purchases and in utility long-term generation purchases (ibid). In addition, two bills in 1991 also looked ahead towards more sophisticated costing of renewables. AB 2198, “required State and municipal electric resource acquisition programs to include a value for the resource diversity provided by renewables” (Sawin 2001, p. 176). And AB 1090 (Hayden, Chapter 1023, Statutes of 1991) “required the CPUC to set aside a specific portion of future capacity for renewable resources until the Commission devised a procurement methodology that valued the environmental and diversity costs and benefits associated with various generation technologies” (ibid.).

In 1993, the BRPU energy auction began. Bidding irregularities led to a suspension of the auctions, based on a motion filed by SCE; this suspension was made permanent in 1995 as a result of a FERC decision. In that decision, mentioned in the Federal section above, the FERC made a determination on a case involving SCE and SDG&E which “disapproved” the BRPU. FERC said that the auction process, which only allowed QFs—instead of all potential generation sources—to participate, in effect “set rates above

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[33] Recall that the ISO4 contracts, which were particularly important to solar and other renewable energy technologies, were supposed to be “interim.”

the current avoided cost of capacity and energy" (Zucchet 1995, p. 37). The CPUC complained that the FERC overstepped its authority in making this determination, as it limited California's ability to engage in resource planning. Although FERC later reaffirmed its decision in the face of this complaint, it did cede that states can pursue favored technologies "as long as such action does not result in rates above avoided cost," as is the case in so-called "externality adders" to avoided cost calculations (ibid., p. 38).[34]

There were several results from the FERC decision. First, no FSO4 contracts were ever implemented (Sawin 2001, p. 177). Second, QFs faced financial problems given the coincidental timing of the FERC decision with the pending 11-year "cliffs" of avoided costs written at 6–9¢/kWh dropping off to 3–4¢/kWh (Allen 2005). Third, the BRPU cancellation effectively stopped "1,500 megawatts of new QF capacity, almost 600 megawatts of which was to be provided by renewables" (ibid). Fourth, California's approach to renewable generation shifted considerably, with the CPUC "proposing that utilities keep and promote their current use of renewable energy through quantity mandates rather than price mandates" (ibid., p. 31). In the restructuring legislation which became effective at the end of 1996:

> "Although general contracts can now be signed between utilities and non-utility producers, there are no long-term contracts, and utilities are not required to purchase power from qualifying facilities." (Allen 2005)

Just prior to this restructuring legislation, in 1995, California issued its first Net Metering Law, SB 656 (Alquist, Chapter 369, Statutes of 1996), which came into effect January 1, 1996. Besides simplifying the grid interconnection rules for PV systems as large as 10 kW, it provided that residential customers operating a "solar electrical generating facility" would be able to receive standard contracts at retail prices for the generation they produced from any utility in the state (Wiser, Pickle et al. 1998, p. 470).[35] As originally established, net metering meant using a "single, nondemand, non-time-differentiated meter to measure the difference between the electricity supplied by a utility and the electricity generated by an eligible customer-generator and fed back to the utility over an entire billing period" (SB 656). Net metering contracts were to be made available to "eligible customer-generators on a first-come, first-served basis until the time that the total rated generating capacity owned and operated by eligible customer-generators in each utility's service area equals 0.1% of the utility's peak electricity demand forecast for 1996" (ibid.).

A series of laws has built upon this initial legislation over the past several years, with a number of provisions applicable to solar energy technologies. In 1998, AB 1755 (Keeley, Chapter 855, Statutes of 1998) added small commercial customers (again, up to 10 kW) to net metering eligibility. It also modified the manner in which net metering would be accomplished, "using a single meter capable of registering the flow of

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[34] AB 2198 and AB 1090, mentioned above, were certainly in the externality adder vein of policy instrument.

[35] According to Sawin (2001, p. 179), "in the past, utilities used the lack of uniform standards to create interconnection barriers to individual systems, with each utility setting different rules."

electricity in two directions," and allowing for "an additional meter or meters to monitor the flow of electricity in each direction" to be installed (AB 1755). In 2000, AB 918 (Keeley, Chapter 1043, Statutes of 2000) provided for customer-generators "taking service under tariffs employing 'baseline' and 'over baseline' rates" or "taking service under tariffs employing 'time of use' rates," to have the net kWh they produced or consumed priced accordingly under net metering. So-called "time-of-use" net metering has proven especially favorable to solar technologies, as these technologies often generate the most electricity at times of peak electricity demand. In 2001, AB 29 (Papan, Chapter 160, Statutes of 2001) raised the eligible system size from 10 kW to 1 MW and expanded the eligible customer-generators to include commercial, industrial, and agricultural customers (Wiser, Pickle et al. 1998, p. 470). In 2002, AB 58 (Keeley, Chapter 836, Statutes of 2002) capped the total rated generating capacity for which the utilities were required to provide net metering contracts at 0.5% "of the electric service provider's aggregate customer peak demand."

The timing of net metering slightly preceded the major efforts to restructure California's electricity sector. The first net metering law was approved by the governor on August 3, 1995, a little more than four months before the CPUC issued its "final" restructuring decision on December 20, 1995. As part of this decision, the CPUC decided to meet existing renewable mandates through a renewables portfolio standard (RPS), rather than simply rely on "green marketing" approaches to electricity customers (Sawin 2001, pp. 484–5). The Renewables Working Group the CPUC set up to help consider RPS implementation details, however, did not unanimously support the RPS, and when the legislature passed AB 1890 (Brulte, Chapter 854, Statutes of 1996) in August, 1996, this foundational bill establishing the renewables approach under restructuring included these dissenters' preferred option, a surcharge-funded program (ibid).

This program, which was initially established to support different categories of renewables in the state "during the four year restructuring transition period starting January 1998," centered on the Energy Commission and what was to become known as the Renewable Resource Trust Fund (RRTF) (ibid., Wiser, Pickle et al. 1998, p. 470). The following bills all played a part in the design of this complex new program to promote existing, new, and emerging renewables: AB 1890 (passed in 1996), SB 90 (Sher, Chapter 905, Statutes of 1997), AB 995 (Wright, Chapter 1051, Statutes of 2000), SB 1194 (Sher, Chapter 1050, Statutes of 2000), SB 1038 (passed in 2002), and AB 135 (Reyes, Chapter 867, Statutes of 2004). The first of these, AB 1890, established a Renewable Energy Program (REP), to be funded by the three IOUs (PG&E, SCE, and SDG&E) collecting a distribution surcharge from their customers. These funds were then to support various categories of renewables, as defined in the legislation. SB 90 took the $540 million the three IOUs were to collect in four years (1998–2001) and placed that money into the RRTF, which was to be distributed in four accounts: (1) the Existing Renewable Resources Account; (2) the New Renewable Resources Account; (3) the Emerging Renewable Resources Account; and (4) the "Customer-Side Renewable Resource Purchase Account" (Wiser, Pickle et al. 1998, p. 471).

The Energy Commission provided additional details concerning the RRTF in late 1997 (the year before it was to begin operating), setting out the percentage of funds to be distributed to the Existing (45%) and Customer-Side (15%) accounts, and establishing that the Emerging account would be unique among the accounts as a buydown rebate program (Sawin 2001, p. 485).[36] The Customer-Side account was to both educate and incentivize customers to purchase renewable energy, either through distributed generation or through the "green power" market. In support of the green power option, all energy service providers were to disclose their fuel sources (CEC 2005, p. 3). In addition, in 1998, a customer credit of 1.5¢/kWh was offered to California customers of renewable electricity generated in California by entities other than utilities, if sold by a "registered electric service provider" (IREC 2006).[37]

In 2000, two bills (AB 995 and SB 1194), extended through 2011 the system benefits surcharge collection at the annual level of $135 million established in AB 1890 (CEC 2005, p. 3). Then in 2002, SB 1038 "authorized the CEC to use these funds for the continued administration and support of the REP from 2002 through 2006"; the "REP retained its basic structure … when it recommenced in 2003" (ibid., pp. 3–4). The four main elements of the REP stayed more or less the same, although with different percentage allocations than in AB 1890: (1) the Existing Renewables Facilities Program (20%); (2) the New Renewable Facilities Program (51.5%); (3) the Emerging Renewables Program (26.5%); and (4) the Consumer Education Program (2%) (IREC 2006).[38] The Existing program offers varying financial incentives "based on the market competitiveness of California's existing renewable technologies" (PG&E 2006). The New program offers financial incentives for the first five years of generation to eligible "projects most likely to become competitive with conventional technologies" (ibid.). The Emerging program authorized in SB 1038 offers both rebates and production incentives to customers with systems of 30 kW or less, with a particular benefit for application of renewables to affordable housing projects of an additional "25% above the standard rebate level, up to 75% of the system's installed cost" (CEC 2005, p. 3). (Systems larger than 30 kW—primarily businesses—receive incentive payments ranging from $1/W–$4.50/W through the Self-Generation Incentive Program (SGIP), which the CPUC

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[36] Figures in a contemporary paper establish the percentages for the New (30%) and Emerging (10%) accounts (Wiser et. al. 1996). The Emerging Renewables Buydown Program (renamed the Emerging Renewables Program in 2003), applied to both PV and STE technologies, among other renewable systems less than or equal to 30 kW in size. The original program helped residents and small commercial establishments by paying "50% of the system cost or $3/W (whichever is cheaper) for the installation of equipment. As prices decline, buy-down payments drop to $1/W or 20% of the system's cost. Payments … continue for four years or until funds are exhausted. To qualify, … systems must primarily offset some or all of the electricity used by the consumer; be grid-connected; have a full, 5-year guarantee; and be installed by an appropriately licensed contractor" (Sawin 2001, p. 485). "Buydown rates vary between $2,000 and $3,600 per kW, depending on the size of the system and the type of technology used" (EIA 2005, p. 10).

[37] In 2000, this credit was reduced to a rebate of 1¢/kWh, with some customers having "a ceiling of $1,000/year" (Sawin 2001, p. 486).

[38] The Customer Credit Program, which had "provided incentives to consumers who purchased renewable energy in the direct access market," was discontinued "pursuant to SB 1038" and reallocated to the Emerging Renewables Program and Consumer Education Program in 2004 (CEC 2005, pp. 3–4).

created in 2001 in response to AB 970 (Ducheny, Chapter 329, Statutes of 2000) (CEC 2005, p. 5)).[39] And the Consumer Education Program offers grants and contracts for public awareness of renewable energy, as well as helps track and verify "renewable energy purchases under the RPS" (Mingyuan 2005; CEC 2006). Finally, AB 135 (2004) "authorized the use of an additional $50 million of RRTF dollars for the Emerging Renewables Program" to assist "in supporting the ongoing demand for rebates" by California customers (CEC 2005, p. 3).

In addition to the support provided to solar and other renewables in the RRTF, in 2001 another set of solar tax credits was established in California. SBX2 17 (Brulte, Chapter 12, Statutes of 2001) established tax credits for solar and wind energy systems under both the Personal Income Tax Law and the Bank and Corporation Tax Law. These credits were to be the lower of "(a) either 15% or 7.5% of the net cost paid" to purchase and install a solar energy system in California, or (b) $4.50 "per rated watt of [rated peak] generating capacity of that same system," up to 200 kW (CEC 2005, p. 2). The 15% credit was available from January 1, 2001 to December 31, 2003; in tax years 2004–2005, the credit was reduced to 7.5% (ibid.). The credit program ended with systems completed before January 1, 2006.

Note that SB 1038, which was so important to the current version of the RRTF, was written with specific mention to another policy instrument that the California legislature was in the process of reviving in 2002: the RPS. In Section 14, SB 1038 establishes that the New program will offer Supplemental Energy Payments (SEPs) "for up to ten years to renewable generators for the above-market costs of meeting the Renewable Portfolio Standard (RPS) requirements" (CEC 2005, p. 2; IREC 2006) This provision was only to become operative if "either, or both, Senate Bill 1078 or Senate Bill 1524 of the 2001–02 Regular Session of the Legislature is enacted and becomes effective on or before January 1, 2003" (SB 1038).

Senate Bill 1078 (Sher, Chapter 516, Statutes of 2002), which established the state's comprehensive RPS, was signed into law in September 2002. It replaced the goal of 17% renewable energy generation by 2006 (established in SB 1038), with a standard requiring "retail sellers to increase the amount of renewable energy in their portfolios by at least 1% per year, toward a target of 20% renewables by 2017" (Del Chiaro 2006). As a result of IOU progress in meeting the RPS, the Energy Commission and CPUC have worked to accelerate this timetable; the current RPS involves the IOUs and municipal utilities increasing their share of renewables by 2% per year, starting in 2003, with a goal of achieving 20% renewable energy generation by 2010 and, ultimately, 33% by 2020 (Haas 2003).

The adoption of renewable technology has been quite successful in recent years in California, and not only at the utility level in pursuit of the RPS. In addition, the SGIP and Emerging Renewables Programs, mentioned above, have been very successful at incentivizing non-utilities to adopt PV. By the end of 2005, the IOUs that administer the SGIP had paid "or reserved $421 million in rebates to solar projects representing

[39] In late 2003, AB 1685 extended the SGIP through 2007. Subsequent CPUC decisions on the California Solar Initiative (CSI), discussed below, modify the technologies eligible for the SGIP starting in 2007 to exclude solar.

113 MW of power since 2001," and the Energy Commission had "allocated $371 million and has provided incentives to over 50 MW of installed systems since 1998" (CPUC D05-12-044, pp. 3–4). Both programs have "encumbered their expected funding allocations, requiring additional funds to be transferred to the programs" and there is a PV waiting list under the SGIP because of excess demand (ibid).

In December 2005 and January 2006, CPUC commissioner Michael Peevey issued two decisions (05-12-044 and 06-01-024) on an "Interim Order Adopting Policies and Funding for the California Solar Initiative" (CSI). The December decision increased the SGIP funding for 2006 by $300 million, using that money to reduce the PV waitlist (created at incentive levels of $3.50/W) by providing reduced incentives to waitlisted projects of $3.00/W and incentives to new applicants of $2.80/W, the same as in the Emerging Renewables Program.[40] The January decision was considerably more comprehensive.[41]

It established a program to "provide up to $2.8 billion in incentives for solar projects of all types and sizes over 11 years" in order to "bring on line or displace 3,000 MW of power" (CPUC D06-01-024). The program's goal is to "provide upfront rebates following installation at levels that reflect a system performance index," although the CPUC will explore performance-based incentives "prior to the January 2007 consolidated CSI," and will authorize "an application fee for CSI projects, which should substantially reduce the number of unlikely projects for which administrators receive applications" (CPUC D06-01-024).[42] The funding source for the CSI is to be utility revenues from gas and electric distribution rates, with budgets in early years projected to be relatively high, dropping off over time "as rebate levels fall and, hopefully, as the market's need for financial support decreases" (ibid.). If demand exceeds targets, the CPUC plans to "automatically reduce incentive payment levels each year by 10% or more," yet leave staff experts with flexibility regarding actual incentive reductions in any given year (ibid).

A number of stipulations regarding funding eligibility were included in the January decision, including:

1. 10% of the funds must be used for projects for low-income residential customers;
2. energy efficiency audits will be required for existing structures to be considered for solar rebates, and new structures will need to demonstrate compliance with energy efficiency standards;

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[40] Unspent funds from the extra SGIP money will be allowed to transfer into the CSI for 2007.

[41] Much of the January decision was based on an Energy Commission/CPUC staff report that came out in June 2005 and was then commented upon by the end of July 2005. The CPUC "delayed action on this matter while the California Legislature considered Senate Bill (SB) 1, which would have established a state program for increased funding for solar technology incentives over ten years" had it passed in August 2005.

[42] In addition to its financing program, the Emerging Renewables Program incorporates a Pilot Performance-Based Incentive Program (PBI) for the installation of new PV systems.

3. projects can be no larger than 5 MW, but unlike the existing SGIP program, they will be eligible for a rebate for that entire capacity;[43]
4. the technologies eligible for incentives will include PV, STE, SWH,[44] and solar heating and air conditioning; and
5. eligible system size will be limited to 100% of historic peak load[45] (CPUC D06-01-024).

Finally, the CPUC stated that it intended to explore technology-push incentives in the area of R&D instead of just the demand-pull incentives of rebates and performance-based incentives.[46] It decided “to allocate up to 5% of each year’s adopted budget to RD&D that explores solar technologies and other distributed generation technologies that employ or could employ solar for power generation and storage or to offset natural gas usage”; it also decided to use some of that money to study and build “market development strategies” (CPUC D06-01-024).

The CPUC’s August 2006 decision triggers the lowering of incentives on a MW threshold basis, rather than a calendar year basis. The MW trigger for incentive adjustments is pro-rated by IOU service territory and by residential/non-residential customer classification. The 2006 Decision also had a set-aside for customers who do not have access to the federal tax credits, providing they sign agreements that they will not enter into third-party financing.

The December 2005 and January 2006 decisions by the CPUC were initially designed to complement a bill under serious consideration in the legislature in both 2004 and 2005, SB 1 (Murray, Chapter 132, Statutes of 2006), the “Million Solar Roofs” bill. Ironically, the version of SB 1 which was signed into law on August 21, 2006, is now designed to complement the CPUC’s CSI decisions. In what is perhaps its most important provision, SB1 raises the cap on net metering from 0.5% of peak aggregate demand to 2.5%, while stipulating that to truly achieve 3,000 MW of solar power from roofs (the estimated capacity of a million roofs), 5% will be necessary (EIA 2005). SB 1 also mandates that solar becomes a “standard option” for buyers of new homes by 2011, requires consideration by the Energy Commission of mandating solar in all new construction, and reduces the CSI budget by $800 million to support municipal utilities in developing their own solar rebate programs (ibid.).[47]

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[43] Recent legislation (SB 1), discussed below, changes this cap to 1 MW.

[44] The January decision created a pilot program for SWH, to be administered by the San Diego Regional Energy Office.

[45] A July 2006 decision changed this to 100% of annual load.

[46] The CPUC categorized policy instruments regarding solar as “a ‘push’ from an incentive program” and a “‘pull’ [from] a program design that encourages technological improvements.” This implies that it considers rebates a technology push instrument.

[47] California has experience with mandating solar in new and existing construction. The existing and new building construction standard, established by the California Department of General Services in consultation with the Energy Commission, requires solar energy equipment installation on all existing state

International: U.S. federal policy in the 1990s and 2000s regarding solar energy is widely perceived to lag that of other nations, particularly Germany and Japan. These nations created innovative programs in this time period that have succeeded in greatly increasing PV capacity; some of these programs have parallels in California actions and those taken by other states. Figure 8 shows the growth in installed PV capacity in several nations in 1990–2001.

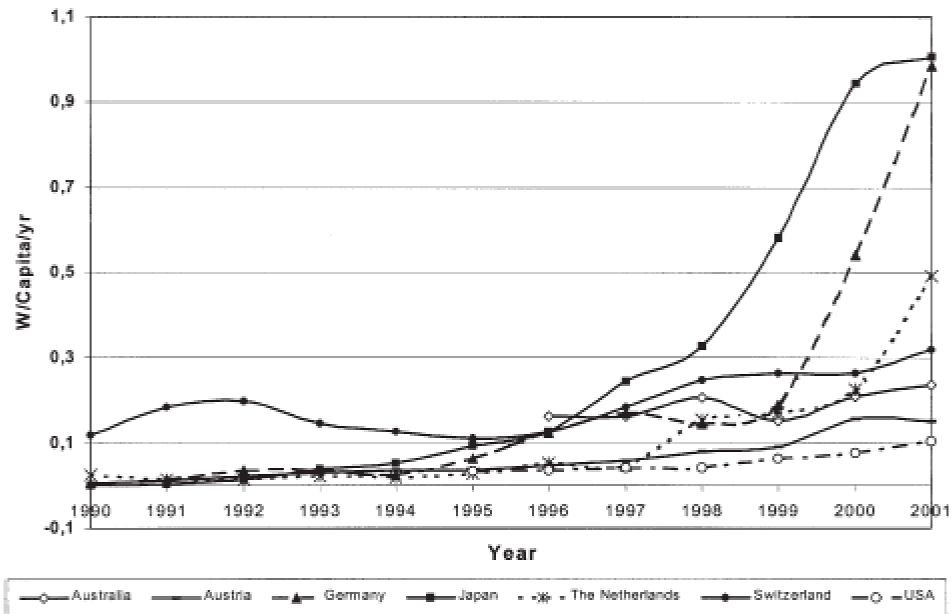

Figure 8. Yearly installed PV capacity per capita over time in various countries, 1990–2001

Source: (Margolis 2002)

Although R&D funding continued to be a part of the portfolio of policy instruments in support of solar technologies in Germany and Japan, the emphasis in the 1990s and 2000s was placed on demand-pull instruments and technological diffusion. German PV installations jumped from less than 50 MW in 1997 to about 400 MW by the end of 2003, while Japanese capacity jumped from less than 19 MW in 1992 to 635 MW by the end of 2002 (Rickerson 2002).

buildings and parking facilities (where feasible), no later than January 1, 2007. It similarly mandates installation in all new state buildings and parking facilities that begin construction after December 31, 2002 (IREC 2006; Mingyuan 2005). These mandates follow years of supporting public agencies in utilizing alternative energy at their facilities. The earliest act in support of this was AB 1942 in 1983, which authorized public agencies to contract with private energy producers for alternative energy projects (Sawin 2001, p. 193). This was amended in 1989 to delete the "limitation that authorized funds for alternative energy systems … in state agencies be used within a ten-year period" (ibid. p. 195).

Germany:
In 1990, the German Federal Research Ministry started to fund the "1,000 Roof" program, which was designed to demonstrate PV for electricity generation on rooftops in Germany. This program heavily subsidized the purchase and installation of PV systems and monitored and evaluated the systems for five years (Margolis 2002; Rickerson 2002). Subsidy amounts were 60% in East Germany and 50% in West Germany, for a total of about $50 million (U.S.$), which was distributed by the State banks (Margolis 2002; Rickerson 2002). Between 1991 and 1994, the 1,000 Roof program is credited with supporting the installation of "2,100 PV systems, with a total capacity of 5.3 MWp" (ibid.).

Also in 1990, the Electricity Feed-In Law (EFL) worked its way through the German Bundestag (Margolis 2002). The EFL required electric utilities to connect renewables to the grid and pay a fixed rate known as the Renewable Energy Feed-In Tariff (REFIT), which was set "equal to 90% of the retail residential price" for wind and solar energy (EIA 2005).[48]

According to Margolis (2002), "by the mid-1990s it was clear that the 1,000 Roofs program had been successful" as a demonstration program, but the EFL "was not sufficient on its own to encourage the rapid expansion of the PV rooftop systems market in Germany." In 1994, a German NGO (Eurosolar) recommended that the 1,000 Roofs program should be multiplied by an order of magnitude to "encourage the development of the PV market (and industry) in Germany" (Margolis 2002). This was incorporated into the platform for the Social Democratic Party that year, and the party worked to pass a "5-year program along the lines of the Eurosolar proposal" in the Bundestag in 1995 (ibid). Although this did not succeed at the time, beginning in 1994, "many Federal States and municipalities became involved in advancing the development of PV panel systems" (Margolis 2002; EIA 2005).

An alliance between the Social Democratic Party and Alliance 90/The Greens in 1998 incorporated the "100,000 Solar Roofs Program," based on the Eurosolar premise, and the bill came into law in 1999 (Margolis 2002). The program, which had a goal of achieving 300 MW capacity by 2004, provided 10-year interest-free loans for PV systems, to be repaid in eight installments after the first two years; "the final installment of 12.5% would be waived as long as the system is still working" (Rickerson 2002; EIA 2005). The German State Bank (KfW) was to administer the loans (which were "approximately equivalent to a 40% direct subsidy"), assume liability for the systems, and "make loan commitments in five days" (Margolis 2002; EIA 2005). Subsidies through the 100,000 Roof program could be combined with other subsidies "at the state and local level, so long as the total level of assistance did not exceed the system's total costs (Margolis 2002). This sometimes proved to be a problem, as rate-based incentives in some cities could combine with the loans to add up to more than the system's total costs; as a result, the program was temporarily halted in these cities in 1999 (Margolis 2002).

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[48] According to Rickerson (2002), "hydropower, landfill gas, sewage gas and biomass producers were guaranteed at least 80% of the retail consumer price."

In 2000, Germany passed the Renewable Energy Law (REL), which established a REFIT mechanism which better reflected plant operational costs than did that established under the EFL, although only for a limited amount of time (EIA 2005). The "feed-in price" for PV, for example, was raised from the equivalent of 8¢/kWh to 51¢/kWh, but that rate was set to decrease annually by 5% in expectation of future cost-competitiveness (Margolis 2002). In addition to setting different, declining buyback rates for different technologies, the REL also established that the grid connection costs for renewable energy technologies are to be taken up by the utilities, "which can pass on the costs to consumers" (Haas 2003). The applications for PV subsidies in 2000 swamped the program, depleting the budget and prompting a temporary (six month) halt in operations until the Bundestag could modify the 100,000 Roofs program later that year. Modifications included: shortening the program's target date by one year to 2003, allocating an extra $20 million (U.S.$), and changing the terms of the loan subsidy (Kurokawa and Ikki 2001). Figure 9 shows the applications filed in the first four years of the 100,000 roofs program.

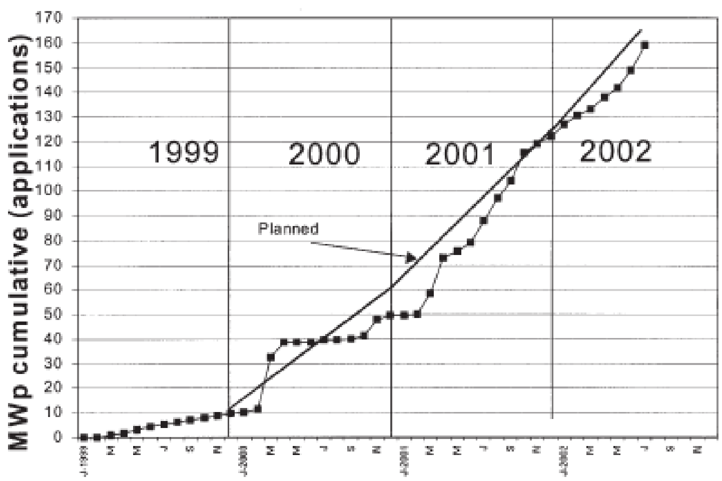

Figure 9. The German 100,000 roofs program: Cumulative applications of the first four years

Source: (EIA 2005)

Japan:

Although Japan continued to strongly support PV R&D in the 1990s and 2000s, this time period is distinguished by the nation's adoption of a number of other policy instruments to support PV including net metering, installation subsidies, and a renewable portfolio standard. It is also distinguished by the growing importance to Japan of promoting solar energy for environmental reasons, rather than simply energy independence. The nation's role as the host of the Third Conference of the Parties to the United Nations Framework Convention on Climate Change in 1997—which resulted in the Kyoto Protocol—was partially responsible for this shift.

In the early 1990s, Japan established the basic structure for net metering. In 1992, the utilities announced a buyback program in which surplus power would be purchased at the same rate as the retail price of electricity (Kurokawa and Ikki 2001). In 1993, the modified "Guideline to Regulate Utility-Connection Technology" established grid interconnection rules.[49]

Also in 1993, the government launched a major R&D project, the New Sunshine Program (NSP), which combined the original Sunshine and Moonlight projects (Jager-Waldau 2004). The major research areas in the NSP included efforts to: mass produce low-cost PV cells, reduce the cost of PV systems, create building-integrated PV modules, and improve PV efficiency (Margolis 2002). The Ministry of International Trade and Industry (MITI, renamed the Ministry of Economy, Trade, and Industry—METI—in 2000) funded this R&D with NEDO directly supervising it. The "New Sunshine Project – 1st Stage," which ended in March 2001, considered PV a "New Energy" technology (other new energies included biomass, solar thermal, wind, and the innovative use of fossil fuels, such as cogeneration, fuel cells, and recycled fuel energy) (Margolis 2002; EIA 2005). The 2000 review of the NSP resulted in the formation of a new PV research program, "Advanced PV Generation" (Margolis 2002).[50]

In December 1994, the "Council of Ministers for the Promotion of Comprehensive Energy Measures" set out government targets for PV in the "Basic Guidelines for New Energy Introduction;" these guidelines were based on a Cabinet Decision in September 1994 (ibid.). The targets for PV installation were aggressive, putting the country on a course to increase PV capacity to 400 MW by 2000 and 4,600 by 2010 (Margolis 2002).[51]

One main path for meeting these targets was also established in 1994, when Japan began residential subsidies for the installation of PV systems through the Residential Monitoring Photovoltaic Power Generating Systems program (sometimes known as the 70,000 Solar Roofs program). Under this program, which was expanded in 1997 and renamed the PV System Dissemination Program as part of Japan's New Energy Law, the Japanese government paid a significant portion of the cost of installing rooftop PV systems if the installer collected data about user needs and efficiency (Haas 2003). As depicted in Figure 10, rebates in the program, which were available to homeowners installing their own PV systems and suppliers of ready-built houses decreased over time (Haas 2003). In addition to decreases on the upper limits of subsidies allowed for systems, the subsidized percentage of investment costs also decreased over time. For example, rebates were 50% of total investment costs in 1994–1996 and about 30% in 1999; by fiscal year 2000, however, a decision was made to switch to a fixed amount of money per kW (Jager-Waldau 2004).

[49] The precursor to net metering was established with an amendment to the Japanese Electric Utility Industry Law in 1990, which simplified installation procedures for PV systems under 500 kW (Kurokawa and Ikki 2001).

[50] NEDO was itself reorganized as an independently incorporated administrative agency in October 2003.

[51] The 2010 target was changed to 5,000 MW as part of the 1998 revision to the Long-Term Energy Supply and Demand Outlook (Kurokawa and Ikki 2001).

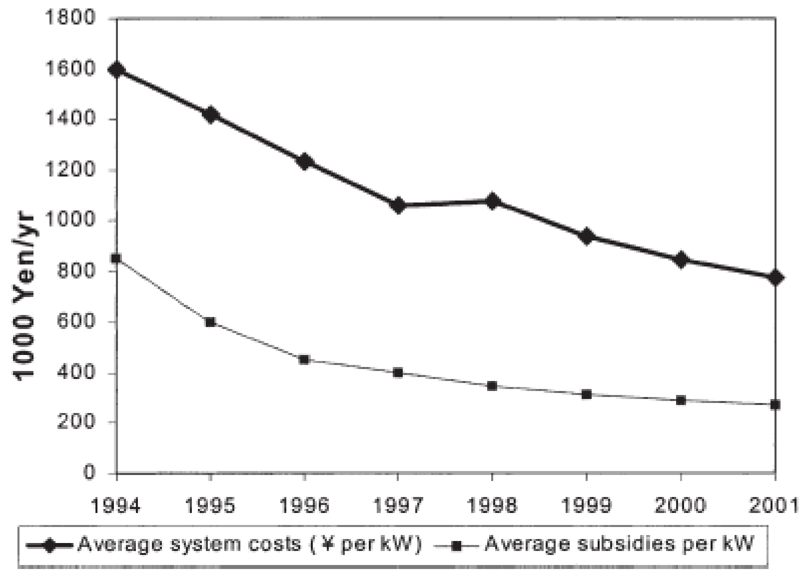

Figure 10. Japanese residential PV promotion program: Development of investment costs and rebates 1994—2001

Source: (Kurokawa and Ikki 2001; Yamaguchi 2001)

Note that the residential PV subsidy program combined, to some extent, "with low-interest consumer loans and comprehensive education and awareness activities for PV," as well as beneficial tax provisions (ibid. p. 285, 294).[52] In addition, housing companies make use of the program—as well as supplemental funds provided by local governments (more than 260 of 3,700 by 2004) —and are promoting sales of products with the PV system as standard equipment (Yamaguchi 2001). Finally, some financial institutions "provide preferential financing at low interest rates for residential PV systems for private use" (ibid. p. 308).

A subsidy program for medium-scale systems, with similar reporting requirements to the residential PV subsidy program, also began in the early 1990s. In 1992, NEDO began the "PV Field Test Project for Public Facilities," which subsidized PV installations in public buildings at one-half the installation cost (EIA 2005).[53] This program, which successfully promoted the installation of 186 systems (4,900 kW), was completed by fiscal year 1997 (Haas 2003). That same year, the "PV Field Test for Public Utilities" program broadened the earlier program's scope to cover PV installations on office buildings and industrial applications (ibid.). In fiscal year 1998, this program was officially renamed the "PV Field Test for Industrial Use" program (ibid.).

[52] The "taxable amount of fixed property is reduced to 5/6 for three years if a PV system is installed." (Haas 2003).

[53] Subsidies of two-thirds the installation cost were provided for "disaster prevention-type applications." (Kurokawa and Ikki 2001).

The goal of both the residential and public facility/industrial use subsidy programs was to reduce the cost of PV system installations (Kurokawa and Ikki 2001). Figure 11 shows trends in market growth and market prices in Japanese PV installations in the 1990s. As a result of these efforts, Japan became “the world leader in the development of grid-connected PV systems” (Jager-Waldau 2004, p. 17).

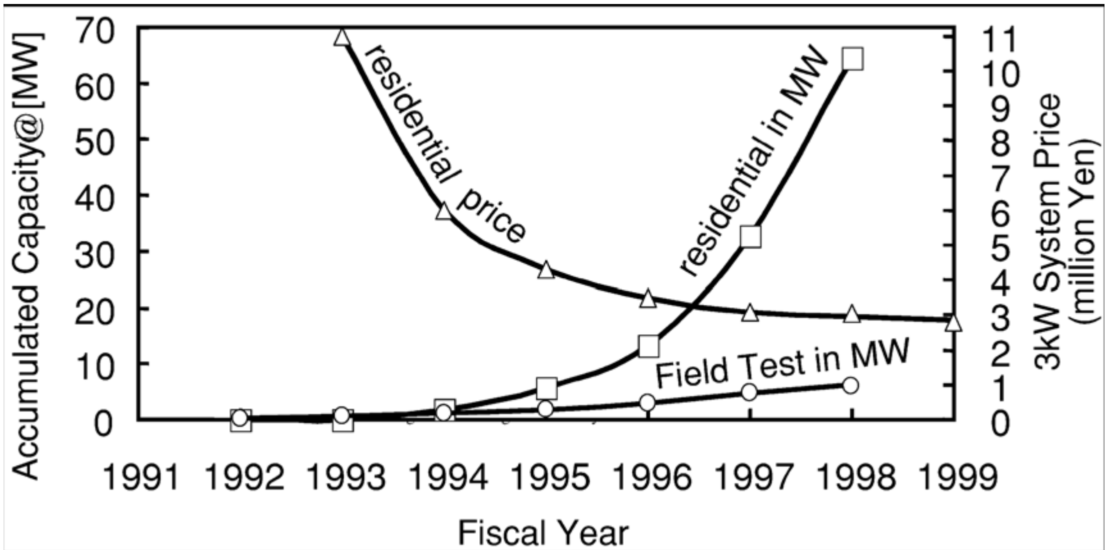

Figure 11. Accumulated PV capacity and price trends related to Japanese PV subsidy programs

Source: (REPiS 2003)

Not all Japanese companies engaged in PV cell research have stayed in the field, however, in part because the New Sunshine Project selected “only those companies showing the best results while receiving promotional funds” for further funding (Ristau 2001). In addition, METI monitors the quality of installations under the various dissemination programs and imposes penalties on poor performers. In one example,

> “In the spring of 2000 it became known that over 20% of solar power systems, which had been delivered throughout Japan by Sanyo Electric between 1996 and 1998 had defects. The METI forced the CEO of Sanyo, Sadao Kondo, to step down…” (ibid.)

In response to Japan’s obligations under the Kyoto Protocol, which came into effect in February 2005, the Japanese government has made two additional pushes which support of solar energy technologies. The more developed program, the “Law on Special Measures for the Utilization of New Energy by Electric Utilities” was drafted by MITI, passed by the legislature (the National Diet) in spring 2002, and entered into effect in April 2003 (Haas 2003). It is an RPS that aims to triple, by 2010, the proportion of the power supply attributed to renewable energy in fiscal year 1999 (a target of 3.2%) (ibid.). Every four years, METI, in consultation with the “Advisory Committee for Natural Resources and Energy,” establishes aggregate eight-year targets for the use of six types of renewable energy: solar, wind, geothermal, small hydro (less than 1,000 kW), and "'sources other than oil that the government specifies,' which may include biomass and waste" (Jager-Waldau 2004; EIA 2005; Ohira 2006). Power producers then set annual sales targets proportionate to their overall size and report the previous year's results to METI.[54]

> "The companies could achieve their targets either by generation of new energy with own facilities, buying electricity from authorized new energy generators or buying surplus from other retailers. The exchange of surplus will be handled by certificates issued by METI. These certificates will be valid for two years and issued for every 1,000 kWh of renewable energies generated. A company that fails to meet its target in the initial year will be allowed to pay METI an amount of certificates equivalent to its annual target in the following year, plus the first year's shortage." (Jager-Waldau 2004)

Maximum fines of one million yen are possible (Ohira 2006).

Finally, Japan's National Space Development Agency (NASDA) has been researching the concept of a solar-power satellite system (SPS) and announced in 2001 that the agency plans to start operating such a system in 2040 (Fukada 2001). According to a press account at the time of the announcement, the SPS will be "capable of generating one million kilowatts per second" via "two gigantic solar power-generating wing panels, each measuring three kilometers" with a 1,000 meter diameter power transmission antenna between them" (ibid). The electricity will then be beamed to earth

> "in the form of microwaves with a lower intensity than those emitted by mobile phones … The receiving antenna on the ground, several kilometers in diameter, would probably be set up in a desert or at sea, and the electricity relayed from there along conventional cables … One economic hurdle so far is that it would cost about 23 yen per kWh to generate power in space compared to nine yen for thermal or nuclear power generation." (ibid.)

1.3. Research Methods

As seen in the previous section, there is a long and complex history of government actions in support of solar energy technologies. There is also considerable complexity in the innovation process underlying the technological changes governments seek to support. A review of the extensive "mainstream" literature on innovation, which dates back at least to Schumpeter (1942), shows that scholars have moved beyond considering the innovation process as a linear model—first made policy-relevant in Bush (1945)—of *basic*, then *applied*, research, followed by *development* and *diffusion*. Instead, the innovation process can be pictured as a set of activities—*invention*, *adoption*, *diffusion*, and *learning by doing*—which overlap and allow feedback between the activities.

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[54] Power producers fall into three categories: (1) the ten general power producers, (2) special power producers which supply power to specific areas using their own generation facilities and transmission lines, and (3) power producer and supplier operators which supply power to commercial-scale customers via the transmission lines of general power producers (Ohira 2006).

In keeping with definitions begun in (Schumpeter 1942), "invention" or "inventive activity" refers to the development of a new technical idea. As stated in (Clarke and Riba 1998), "an invention is an idea, sketch, or model for a new device, process or system." "Adoption," (sometimes referred to as "innovation," although not in this report in order to avoid confusion with the overall innovation process) is the first commercial implementation of a new invention. "Diffusion" refers to the widespread use of a commercial innovation, and is often studied as a communication process between current and potential users of a technology (Rogers 1995). Finally, "learning by doing" refers to the post-adoption innovative activity that results from knowledge gained from difficulties or opportunities exposed through operating experience (this activity is sometimes alternatively referred to as "learning by using" or "reinvention"). Studies show that operating personnel and their contacts with other researchers are important sources of new ideas and technological advances (for a discussion, see Cohen and Levin (1989)).

Figure 12 depicts the role of government actions on the innovative activities just described in the case of an environmental technology. Note that these innovative activities are conducted by a network of actors embedded in standard business relationships with suppliers, buyers, competitors, and substitutes. Central to this network, as it is to Figure 12, is government, which may influence any of the stages of the innovative process, including invention, adoption and diffusion, and learning by doing. Arrows in the figure point to the primary types of government intervention at each stage. These arrows are labeled either "technology push" or "demand pull," labels which link the figure to one of the themes of the mainstream innovation literature: the relative importance in driving innovation of supporting particular technologies (reducing their price on the supply curve) versus responding to market needs (increasing their quantity on the demand curve). Note that the activities in Figure 12 are enclosed by a circle demarcating the innovative process; on the outside of the circle are the outcomes of the full innovative process, which can be often be observed as improvements in technical performance as well as cost reductions.

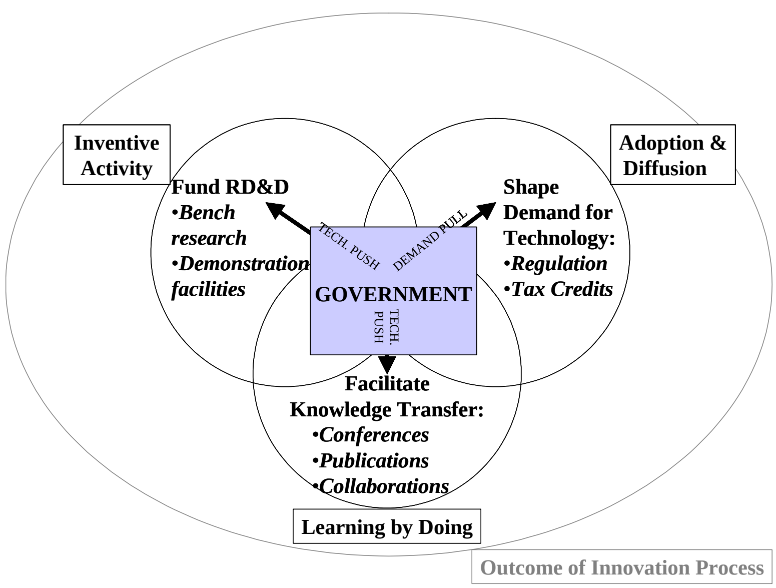

Figure 12. The role of government actions in the innovation process in an environmental technology

The mainstream economics of innovation literature does not generally catalogue government actions by their effects on innovation, despite having recognized environmental regulation as an inducement for technological change for decades (See Rosenberg 1969, for example). The much younger "environmental technology" literature (see Kemp 1997 for a review), however, has been particularly concerned with how the details of government actions—characteristics such as regulatory stringency, flexibility, and uncertainty—affect environmental technological innovation. This literature, while considerably smaller than the mainstream innovation literature, is possibly more diverse, encompassing theoretical studies, a few large empirical studies, and a number of case studies scattered among various disciplines. Case studies are particularly valuable in understanding the effects of government actions on innovation because they allow scholars to be attentive to the details of different government actions and how they affect innovative organizations.

This report follows a modified case study approach, in which the details of government actions matter, but the results can be compared and contrasted against other environmental technology cases because they use the same methodology: an integration of several repeatable quantitative and qualitative methods that are well-established in the mainstream innovation literature. It follows the example of Taylor (2001), which used the same approach to investigate innovative activities and outcomes in sulfur dioxide control technologies for coal-fired power plants. This approach provides a more realistic understanding of the innovation process than any single method would be able to provide alone (for useful reviews of methodological issues in the study of technological innovation, see Cohen and Levin 1989; Schmoch and Schnoring 1994). It also provides the foundation for concrete comparative analyses across cases. Figure 13 illustrates the various research methods used in this report: analyses of United States patents, research laboratory activity, technical conference proceedings, experience curves, and interviews with influential experts.

Note that no method speaks to only one innovative activity. Patents, for example, measure inventive activity, but they are also important to the understanding of adoption and diffusion, as inventors typically file patents because they expect to market their inventions. Research laboratory activity speaks mainly to RD&D funding, but is also important for understanding the ways that government was able to facilitate knowledge transfer across innovative actors. Technical conferences provide a forum for all the various innovative activities; they also provide a dataset to understanding changing researcher networks over time. Experience curves reflect diffusion along their x-axes, but provide deeper insights into the outcomes of the full innovative process via their y-axes. Finally, expert interviews provide insight into all the various innovative activities as well as the outcomes of innovation.

The following short sections provide sketches of the various research methods used in this report. More detail on each method is provided in the appendices.

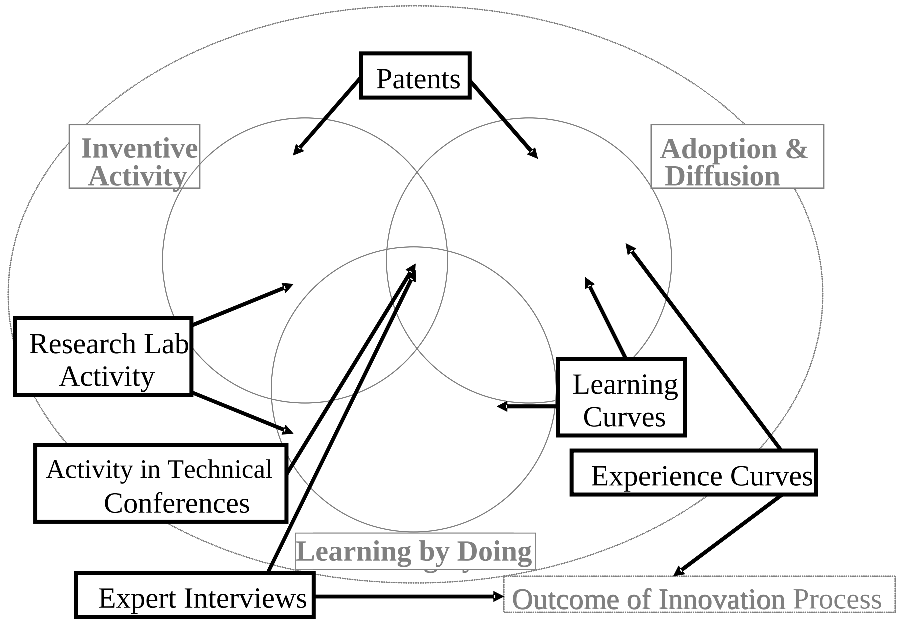

Figure 13. Research methods used in this report

1.3.1. Patent Activity Analysis

Researchers have long used patents as a measure and descriptive indicator of inventive activity (Griliches 1990). Patents provide detailed and publicly accessible technical and organizational information for inventions over a long period of time. Studies have shown that patenting activity parallels R&D expenditures by firms; this relationship is particularly useful when detailed R&D information for an industry is unavailable. In addition, studies have shown that patenting activity can be linked to events external to a firm such as government actions.

A central challenge of using patenting activity as a metric of inventive activity is to identify a set of patents from the more than six million patents granted by the United States Patent and Trademark Office (USPTO) to serve as the dependent variable without excessive "undercounting" (including too few relevant patents) or "overcounting" (including too many irrelevant ones). Based on the methodology of (Taylor 2001), this report uses two approaches to patent identification which draw on two main sources of data: the USPTO patent database from 1887–1997 and an interview with the primary USPTO examiner of each set of technologies.

In the first of these approaches, the USPTO classes used to develop prior art—earlier patents whose claims are legally determined by the patent examiner to be closely related to the claims in the citing patent—are elicited from the patent examiner.[55] These classes are then used to generate a "class-based" dataset of patents issued from 1887–2001 that is relevant to each technology and consistent for over 100 years. The tradeoff for the length

[55] Patents are assigned to a "primary class" and can be also assigned to one or many secondary, or "cross classes."

of this dataset is that it is less certain with respect to undercounting and overcounting than are other approaches to patent analysis, such as the next method described.

In the second approach used in this report, a more targeted patent dataset is generated based on an electronic search for relevant keywords in the abstracts of all patents granted since 1976 with file dates ending in 2002 (to avoid lag effects).[56] This search is put together iteratively, so as to balance overcounting with undercounting. Once the search is finalized and the dataset created, content analysis is performed on the resulting "abstract-based" dataset for each technology in order to eliminate irrelevant patents, thus ensuring that this dataset is as refined as possible.

As discussed later in this report, these datasets are analyzed graphically and through expert interpretation. For more detail on patent dataset construction for each technology case, see Appendix A.

1.3.2. Expert Elicitations

This report also incorporates structured interviews with experts representing a variety of organizational backgrounds and affiliations involved in each technology. Experts are identified primarily by the length and degree of their participation in conferences for each technology and the range of institutions they represent (including those of industry, government, and academia). Additional experts are identified by recommendations of the initial set of experts interviewed.

As part of the interview protocol, experts are asked about performance, cost, and research and development trends, in part to calibrate responses. Expert opinions on key technological developments and government actions are also elicited, as are their opinions on the importance of patents and particular conferences to the industry and the development of each technology. For more details, see Appendix B.

1.3.3. Analysis of Knowledge Transfer Activity

As noted earlier, the diffusion of information is important in the innovation process. To study the influence of government activity in this area, this report uses two additional methods of analysis centered on annual conferences held on a regular basis and viewed as vital to the development of each technology.[57] The first method is technical content analysis and graphical representation of activity levels in each conference over time (for more details, see Appendix C). The second involves mapping a co-authorship network and analyzing it in order to capitalize on previous innovation research showing that networked organizations have better opportunities to benefit from knowledge transfer (Taylor, Rubin et al. 2003).

1.3.4. Experience Curve Analysis: Performance and Cost

Key outcomes of the innovation process include improvements in the overall performance and cost of each technology over time. This report analyzes the rate of

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[56] Grant dates were used because systematic electronic keyword searching is only possible for USPTO patents granted after 1975.

[57] Technical conferences and consortia are particularly important knowledge transfer mechanisms.

technical improvement for new systems using the concept of an experience curve, in which a performance or cost variable is displayed as a function of total cumulative production of the technology. Data are very specific to the underlying cases; therefore, the construction of these curves will be discussed in more detail in the technology-specific chapters that follow this introductory chapter.

2.0 Photovoltaic Cells

This chapter focuses on the role of government actions in influencing innovation in photovoltaic (PV) cells. The chapter includes: (1) an overview of the technology, including major developments; (2) an assessment of inventive activity and its relationship to government actions, as addressed through analysis of patenting activity; and (3) a consideration of the importance and dynamics of knowledge transfer in the development of PV cells, as addressed by expert interviews and a graphical and network analysis of conferences pertinent to the technology. Following this treatment of the innovation process and its relationship to government actions, the chapter concludes with a treatment of the outcomes of innovation, as measured through experience curves relating technological diffusion to performance and cost improvements.

2.1. Technology Overview

Solar energy reaches the earth in the form of electromagnetic waves, "which also exhibit the behavior of particles, called photons" (Rubin 2001). As photons hit a PV cell, they energize electrons held in chemical bonds in the cell, which then break free of their bonds. If the electrons flow in one direction, as they do in semiconductor materials, they create a current; this phenomenon is known as the "photoelectric effect."

Silicon is the classic semiconductor material. Its "latticed crystalline structure" consists of:

> "silicon atoms bound to each other by four valence electrons. Adding small amounts of impurities to this lattice structure (a process called doping) creates the electrical properties desired. Thus, replacing a silicon atom with an atom having five valence electrons, such as arsenic or phosphorous, leaves one electron free to conduct current. This electron-rich material is called an n-type semiconductor. Similarly, doping silicon with atoms having only three valence electrons, such as boron or gallium, produces a p-type semiconductor with a deficiency of electrons. The missing electrons act like "holes" that can be filled by excess electrons from the n-type materials when the two materials are bound together to form a junction. … In PV applications, the photon energy of sunlight is sufficient to excite free electrons and allow them to cross the junction." (Rubin 2001, p. 222-3)

Figure 14 presents a schematic of a PV cell, including its connection to the electrical transmission system. The "arrays" illustrated in the figure are collections of "panels," which are themselves collections of "modules" of dozens of PV cells. There are a number of technologies involved in connecting the arrays to the electrical transmission system; these are called the "balance of system" (BOS) in a solar application. In the United States, typical BOS technologies include: "structures for mounting the arrays," "power-conditioning equipment that adjusts and converts the DC electricity [generated by the cell] into the proper form and magnitude required by an alternating-current (AC) load," and "storage devices, such as batteries, so PV-generated electricity can be used during cloudy days or at night" (EERE 2006a).

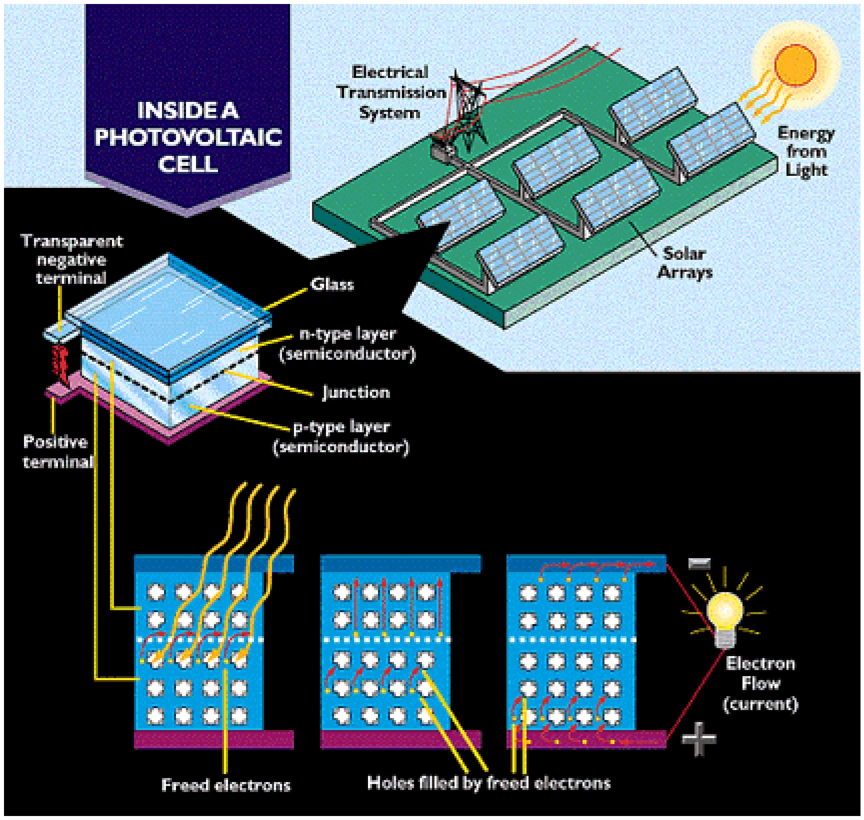

Figure 14. How a PV cell works

Source: (AZSC 2006)

Until recently, the primary market for PV cells has been “niche applications where PV power can replace or supplement conventional electric power at the customer end of the system” (Rubin 2001, p. 223). Figure 15 shows the world market for PV over time, according to six application types: (1) consumer products; (2) commercial PV/diesel; (3) off-grid residential and rural; (4) small grid-connected; (5) communications and signal; and (6) central >100kW.

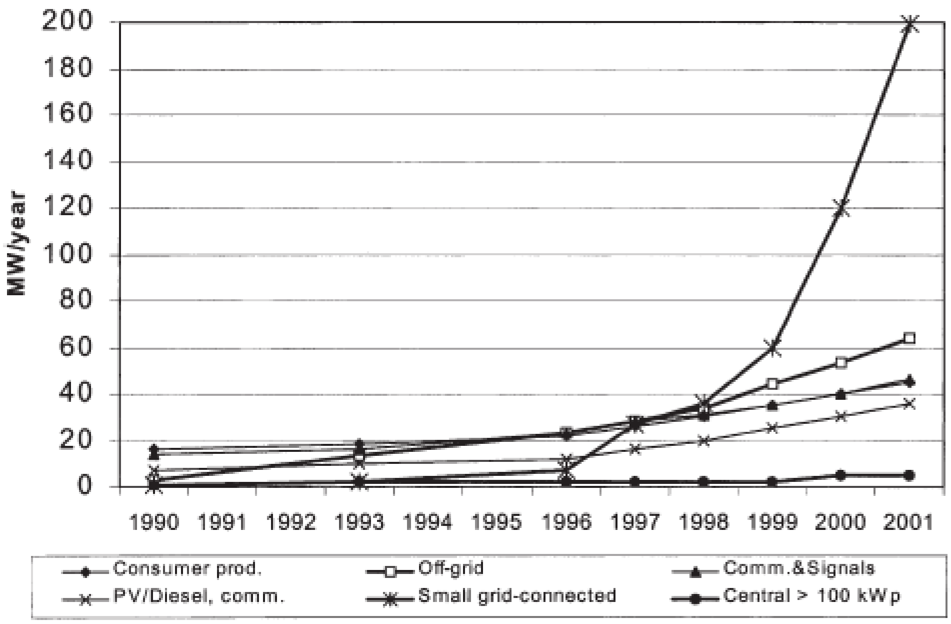

Figure 15. The development of the world market for PV by product category, 1990–2001

Source: (Haas 2003)

The "consumer products" market "includes all applications for power consumer electronics and other small, less than 20 W devices, including lights, signs, security systems, and portable power" (Maycock 2004a, p. 47). The "commercial PV/diesel" market involves "the concept of using the fuel in a diesel or gasoline generator as the storage for a PV system" (Maycock 2004a, p. 54). The "off-grid residential and rural" market consists of "micropower" energy sources supplying electricity needs for homes and communities that are not connected to a central electricity grid. The "small grid-connected" market, which has become the dominant PV application only since 1999, serves residences in Germany and Japan, primarily, but has been making inroads in recent years in other nations as well.[58] The "communications and signal" market, which has been described as "the backbone of the PV industry" as late as 2004, consists of worldwide applications of PV to such applications as "microwave repeaters, TV translators, radio-telephones, educational TV, mobile radios, remote signaling, [and] telemetry" (Maycock 2004b, p. 52). Finally, the "central >100 kW" market consists of three parts: (a) large systems that "proved that PV systems could be built that provided energy of adequate quality to be used in the distribution grid; (b) projects that demonstrated that PV systems can serve "critical loads when located at the end of the distribution system near the peak demand" for electricity; and (c) projects that displace "'sun-belt' coal and gas" with "an 'economic,' renewable, environmentally clean generation option" (Maycock 2004b, p. 59).

[58] For a better feel for the international PV market, see Figure 8, which depicts the annual installed PV capacity per capita in various countries between 1990 and 2001.

As noted in Table 1 (in the introduction to this report), electricity generated by PV cells is considerably more expensive than electricity generated by STE, wind power, large hydropower, nuclear power, or fossil fuel-based power sources. As a result, PV provides only a small fraction of overall electricity consumed worldwide. Yet costs have come down dramatically, as illustrated in Figure 16, as PV cell efficiencies have risen, as illustrated in Figure 17. Note that efficiencies measured in controlled conditions in laboratories are roughly double the efficiencies of installed PV modules.[59]

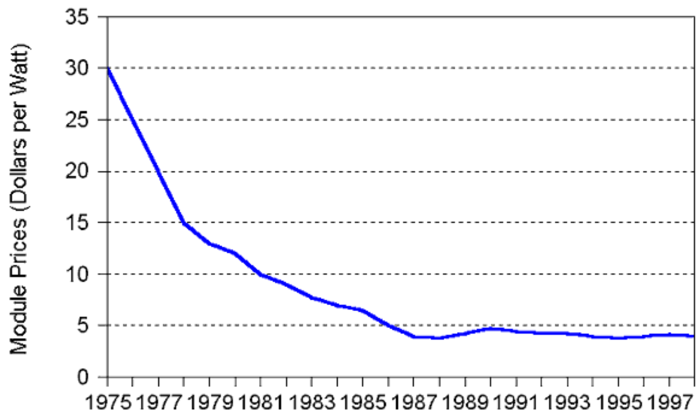

Figure 16. PV module prices, 1975–1998

Source: (Maycock 1999)

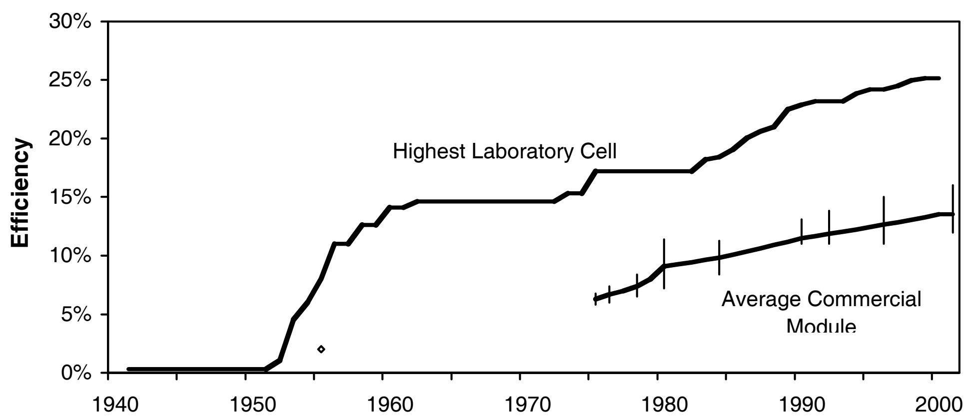

Figure 17. Efficiency of laboratory PV cells and commercial modules

Source: (Maycock 2004b)

[59] The energy conversion efficiency of a PV cell is the ratio of the maximum output electrical power divided by the input light power under "standard" test conditions. The "standard" solar radiation (known as the "air mass 1.5 spectrum") has a power density of 1,000 watts per square meter (W/m^2). Thus, a 10% efficiency solar panel 1 m^2 will produce approximately 120 watts (W) of peak power.

Many researchers believe that the large improvements in cost needed to make truly cost-competitive electricity from PV cells will necessitate a move to materials other than silicon, which dominates the commercial market and has considerably higher efficiencies than its substitute cells.[60] Figure 18 shows world PV module production by the type of cell technology. Note that the introduction of amorphous silicon spurred a new interest in "thin-film" technologies, which are considerably cheaper (and less efficient) than traditional PV cells.

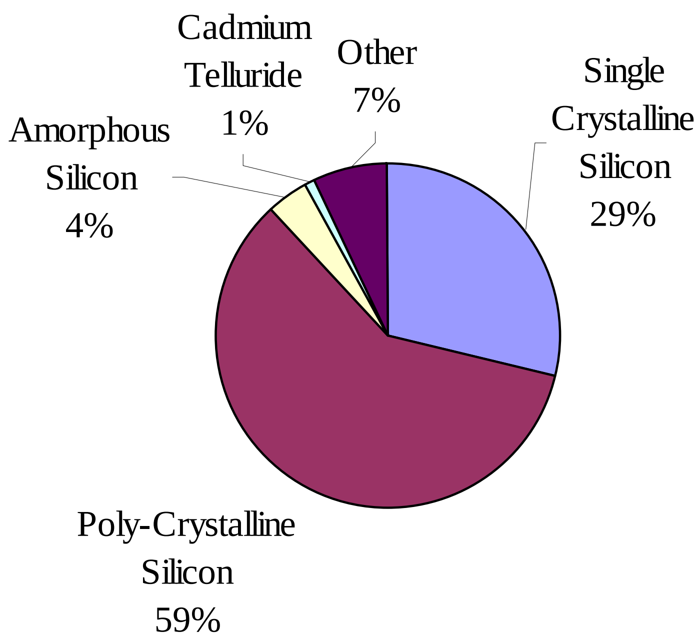

Figure 18. 2004 World PV module production by type of cell technology

Source: (Maycock 2004b)

The U.S. government has been tracking PV cell manufacturing in "shipments" data going back to 1982. Table 4 compiles much of the data on PV cell and module shipments over time, including: the number of U.S. companies manufacturing PV cells and modules, the type (crystal silicon or thin-film) of PV cells shipped, whether cells and modules are imported or exported, and the prices of cells and modules. Table 5 characterizes the U.S. PV industry by the total number of companies engaged in specific PV-related activities.

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[60] This push for lower costs and higher efficiencies has also driven PV research in recent years toward organic and nano-structured materials.

Table 4. PV cell and module shipments by type, trade, and prices, 1982–2004

		Shipments			Trade		Prices	
	U.S. Companies Reporting	Crystalline Silicon	Thin-Film Silicon	Total	Imports	Exports	Modules	Cells
Year	Number	Peak Kilowatts					Dollars per Peak Watt	
1982	19	NA	NA	6,897	NA	NA	NA	NA
1983	18	NA	NA	12,620	NA	1,903	NA	NA
1984	23	NA	NA	9,912	NA	2,153	NA	NA
1985	15	5,461	303	5,769	285	1,670	NA	NA
1986	17	5,806	516	6,333	678	3,109	NA	NA
1987	17	5,613	1,230	6,850	921	3,821	NA	NA
1988	14	7,364	1,895	9,676	1,453	5,358	NA	NA
1989	17	10,747	1,628	12,825	826	7,363	5.14	3.08
1990	[3] 19	12,492	1,321	[3] 13,837	1,398	7,544	5.69	3.84
1991	23	14,205	723	14,939	2,059	8,905	6.12	4.08
1992	21	14,457	1,075	15,583	1,602	9,823	6.11	3.21
1993	19	20,146	782	20,951	1,767	14,814	5.24	5.23
1994	22	24,785	1,061	26,077	1,960	17,714	4.46	2.97
1995	24	29,740	1,266	31,059	1,337	19,871	4.56	2.53
1996	25	33,996	1,445	35,464	1,864	22,448	4.09	2.8
1997	21	44,314	1,886	46,354	1,853	33,793	4.16	2.78
1998	21	47,186	3,318	50,562	1,931	35,493	3.94	3.15
1999	19	73,461	3,269	76,787	4,784	55,562	3.62	2.32
2000	21	85,155	2,736	88,221	8,821	68,382	3.46	2.4
2001	19	84,651	12,541	97,666	10,204	61,356	3.42	2.46
2002	19	104,123	7,396	112,090	7,297	66,778	3.74	2.12
2003	20	[R] 97,940	10,966	109,357	9,731	60,693	3.17	1.86
2004[P]	19	159,138	21,978	181,116	47,703	102,770	2.93	1.92

Source: (EIA 2006a, Table 10.5)

Table 5. Companies involved in PV-related activities in 2004, by type of activity

Type of PV-Related Activity	Number of Companies
Cell Manufacturing	12
Module or Systems Design	18
Prototype Module Development	13
Prototype Systems Development	9
Wholesale Distribution	16
Retail Distribution	10
Installation	6
Noncollector System Component Manufacturing	3

Source: (EIA 2006b, Table 57)

Finally, Figure 19 gives a sense of the changing world production of PV cells and modules. Note that although U.S. companies led the world market in 1996, by 1999 they were second to Japanese companies in terms of total production. By 2002, they were third to European companies (second) and Japanese companies. And by 2003, companies in the rest of the world were closing the gap with U.S. companies.

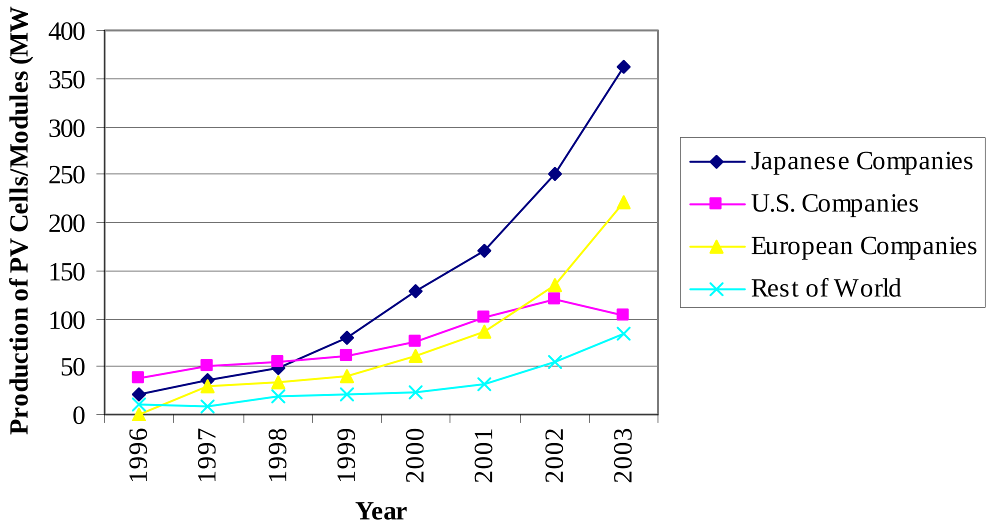

Figure 19. World PV cell/module production, 1996–2003

Source: (Maycock 2004b, Figures 18, 20, 21, and 22)

2.2. Government Actions

The complexity of the solar policy history presented in the introduction to this report—which is in part due to the fact that many of the policy instruments designed to promote solar over the years applied to more than one solar technology—prompted an appeal to experts to sort through the relative importance of various government actions on technological innovation in PV.[61]

Table 6 and Figure 20 compile the responses of the experts interviewed for this report on this issue. Experts ranked government actions on a scale of 1–5, with 5 having the most important effect (negative or positive) on the industry and the development of the technology.[62] The results indicate that initiatives in Germany and Japan are considered quite important to innovation in the PV industry (more so than actions in the United States). In addition, R&D funding, regardless of nation of origin, is considered relatively more important to PV than many other initiatives.

[61] Appendix B details the procedure with which experts where selected, as well as the interview methodology and protocol.

[62] More detailed data is given in Appendix B. The variance on respondent rankings was fairly uniform except for the policies considered most and least important. According to expert opinion there were four key policies during the past 30 years.

Table 6. Expert opinion of importance of government actions to innovation in PV

Government Action	Expert						Average Score (Scale 1–5, with 5 as most important)
	A	B	C	D	E	F	
2000 Germany “Renewable Energy Law” (50¢/kWh)	4	4	5	5	5.5	5	4.8
1950–2005 United States Federal R&D	4	5	4	5	5	3	4.3
1993 Japan “New Sunshine Project” (declining rebates)	4	4	4	5	5	4	4.3
1998–present CEC and CPUC “buydown” rebate programs	4	2	3.5	5	5	4	3.9
1974 Japan “Sunshine Project” (mainly PV R&D)		5	5	4	5	4	3.8
mid-1990s state regulatory changes, such as net metering	5	2		4	4	4	3.8
1993 SMUD PV Pioneer 1 and 2 (bulk purchases)	4	3	4	3	2	5	3.5
1992–present PV business tax credit (10%)	3	2	4	3	3	3	3.0
1990 Germany electricity feed law (similar to PURPA)	4	2	4	4		3	2.8
1978 Public Utilities Regulatory Policy Act (PURPA)	4	1	2	4	2	2	2.5
1997–present 21 other state RPSs and 2 solar set-asides.		2	4	2	4		2.0
1975–84 JPL Flat Plate Solar Array Project (bulk purchases)		1	1		3	5	1.7
2002 CA RPS		2	4	1	3		1.7
1978-85 Federal tax credits (25% increasing to 40%)	3	1	2	1	1	1	1.3
1981–85 Standard offer contracts for PURPA, (~11¢/kWh)		2	2	1	1	3	1.3
1981–86 Energy business tax credit (25%)		2	2	1		1	0.9
1974–83 Warren-Alquist residential tax credit (10%)		1		1			0.3

2.3. Inventive Activity

Two metrics are often used in the economics of innovation literature to give insight into inventive activity: R&D funding is used as an input metric, while patents are used as an output metric. This section will only treat the analysis of patenting activity in PV, as the introduction chapter to this report discusses various solar energy R&D programs in the United States, California, Germany, and Japan. Figure 1, Figure 3, Figure 4, Figure 6, and Figure 7 all contain national solar energy R&D data.[63]

[63] Preliminary work shows that California’s solar energy R&D is not insignificant, although it has proven to be too difficult to compile into a comprehensive time-series in time for the publication of this report.

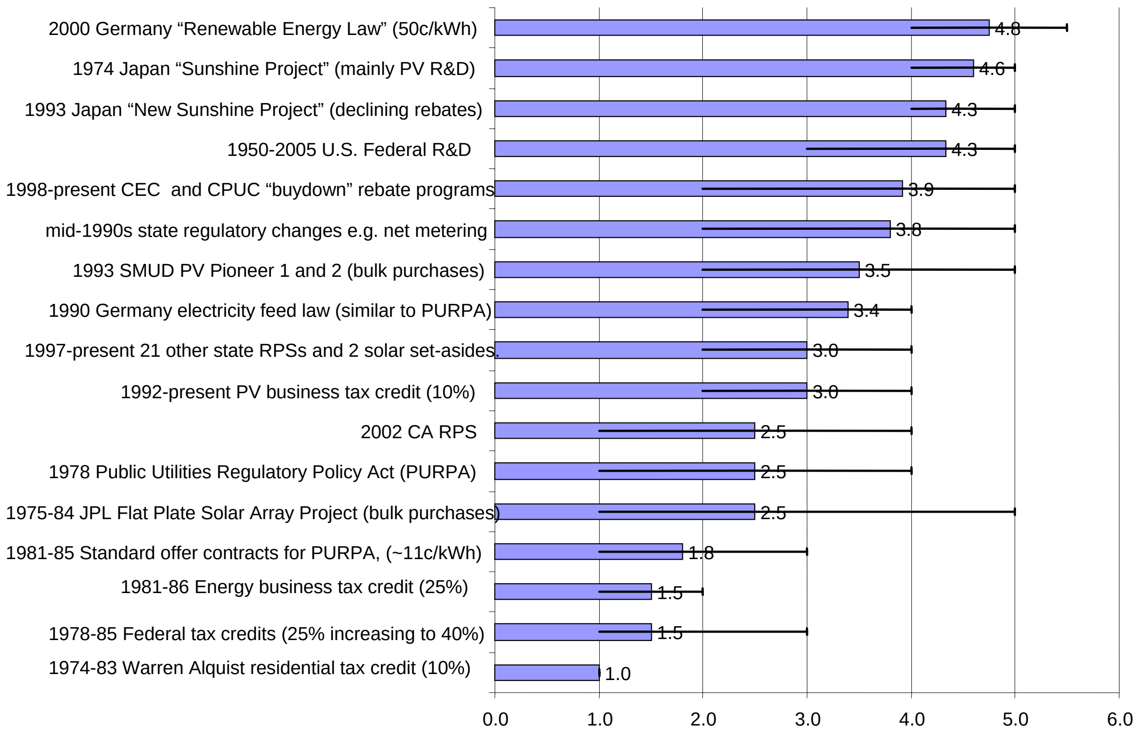

Figure 20. Expert ratings of policies relevant to PV

As outlined in the introduction to this report, two patent datasets—a “class-based” dataset and an “abstract-based” dataset—were created for this analysis using two different approaches to manipulating patent data. Details on the construction of these datasets can be found in Appendix A and in Section 1.3.1, of this report.

2.3.1. Datasets

The class-based dataset of PV patents netted 4,956 patents granted between 1858 and 2002. Figure 21 portrays this dataset according to the patent application date, which is the earliest date that can be consistently tied to the inventions that are granted patents. As there is generally a two-year lag between the patent application date and the date the patent is granted, the dataset in Figure 21 ends in 2002 (as do most of the patent figures in this report). Note that this dataset is not “clean,” as patents in this figure were not coded for relevance to PV.

Although the class-based dataset is consistent for over 100 years, and thus, can be used to relate patenting trends to the timing of long-past government actions related to the technology, the tradeoff for the length of this dataset is that it is less certain with respect to under-counting and over-counting than are other approaches to patent analysis. As in the other technology cases in this report, an “abstract-based” was created to complement the class-based dataset and in part.

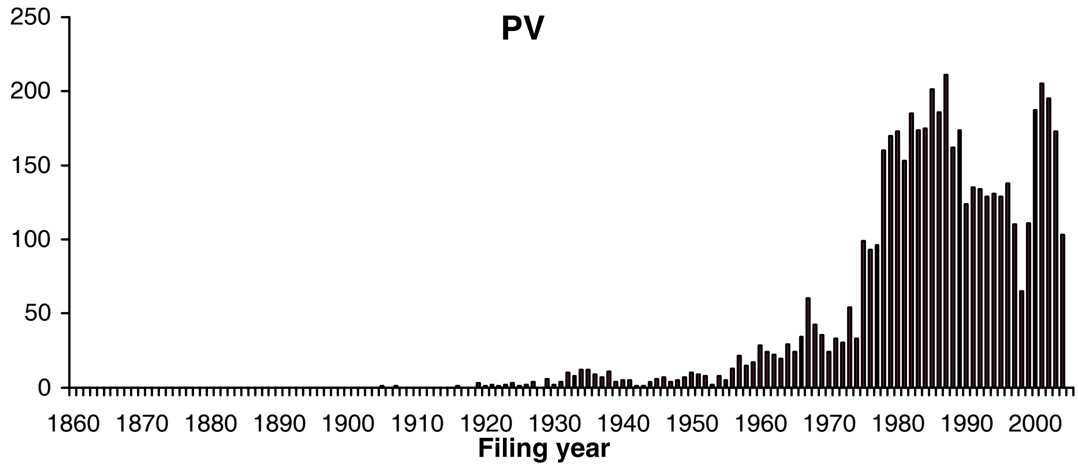

Figure 21. Class-based dataset of PV patents, by application date, 1858–2002

The abstract-based approach to creating a patent dataset for PV netted 13,913 patents granted between 1975 and 2002. Figure 22 shows the abstract-based patent dataset for PV, according to the patent application date. Note that this dataset is not "clean," as patents in this figure were not coded for relevance to PV.

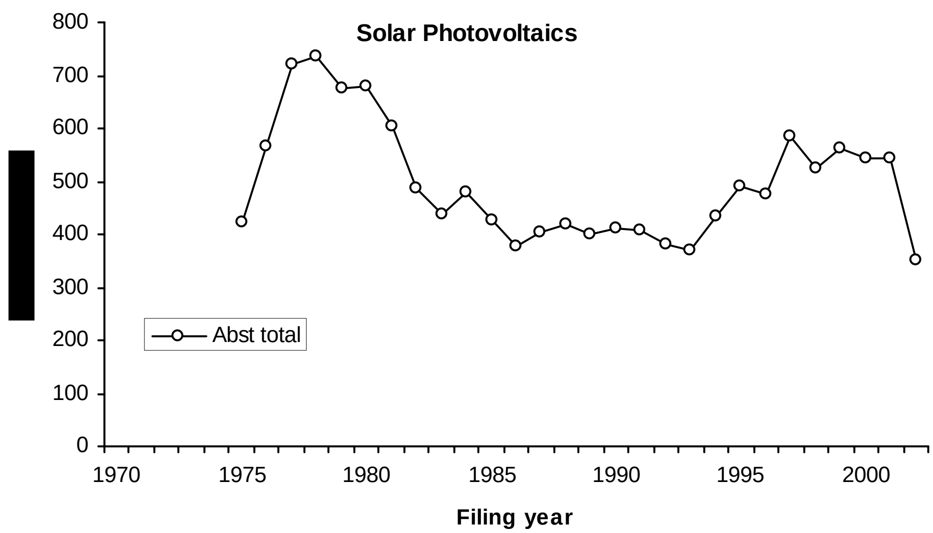

Figure 22. Abstract-based dataset of PV patents, by application date, 1975–2002

It was impractical to code this large dataset manually; instead, a sample of four years of patents—approximately 2,000 patents filed in 1976, 1988, 1998, and 2000—was coded for PV-relevance. The result was that between 52% and 82% of the patents in each year were found to be not relevant to PV. The main reason for this high count of irrelevant patents is the inclusion of the term "photoelectric" in the search. Since a large number of abstracts for PV patents use the term "photoelectric" but not "photovoltaic" or "solar," the term had to be included in the search or it would have undercounted the patents. Unfortunately, a significant number of patents in the electronics industry, particularly in later years in the dataset, include this term but are not relevant to PV; devices using photoelectrical sensors were a particular problem in this regard.

The high percentage of irrelevant patents in the abstract-based search, as well as the high variance in this percentage and the fact that full manual coding of the search was unfeasible, means that analyses in this PV chapter—unlike the STE and SWH chapters—are based on the class-based dataset. Again, this dataset is not "clean," as it has not been coded for relevance to PV.[64] It does, however, correlate well with the sample of four "clean" years from the abstract-based dataset. This relationship is depicted in Figure 23.

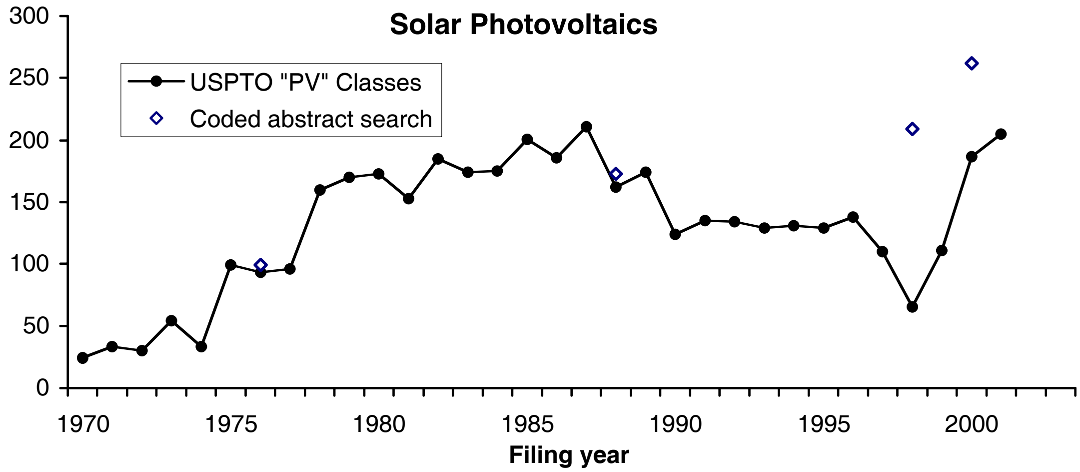

Figure 23. Class-based dataset of PV patents by application date, 1970–2002, with coded sample of abstract-based PV patents in 1976, 1988, 1998, and 2000

2.3.2. Descriptive Statistics

Table 7 shows the top ten patent holders in the PV class-based dataset; none of the top ten patent holders is a government, despite many years of government subsidies for R&D in PV. Five of the firms in Table 7 are Japanese, four are American, and one is German. Note that none of the U.S. companies in the table are headquartered in California. Solarex is the only company on this list that exclusively produces photovoltaics.

Table 8 provides a more comprehensive sense of patent ownership in the PV class-based dataset. The percentage of patents held by the top ten patent holders identified in Table 7 (56.9%) is included in Table 8 for purposes of comparison to the percentage of patents held by individuals (13.1%) and California-based inventors (14.5%).

[64] Coding for relevance for the electronically available PV patents (issued since 1975) is a necessary next step in this analysis. It is considerably less time-consuming to code this subset of class-based patents, however, than all of the class-based patents, which are available in much less accessible forms.

Table 7. Top ten patent holders in the PV class-based dataset

Assignee	Country	# of Patents	% of Total
Canon Kabushiki Kaisha	Japan	383	8.7
Energy Conversion Devices, Inc.	United States	101	2.3
RCA Corporation	United States	92	2.1
Sanyo Electric Co., Ltd.	Japan	89	2.0
Semiconductor Energy Laboratory Co., Ltd.	Japan	88	2.0
Siemens Aktiengesellschaft	Germany	76	1.7
Atlantic Richfield Company	United States	72	1.6
Sharp Kabushiki Kaisha	Japan	67	1.5
Mitsubishi Denki Kabushiki Kaisha	Japan	66	1.5
Solarex Corporation	United States	57	1.3
		Total	56.9%

Table 8. Patent ownership in the PV class-based dataset

Patent Ownership	Proportion in PV Class-Based Dataset (%)
Top 10 Assignees	56.9
Individuals	13.1
California Inventors	14.5

Figure 24 shows all patenting activity in the class-based PV dataset between 1976 and 2001, according to the inventor nation-of-origin. Note that Japanese patenting activity, by file date, overtook U.S. patenting activity in 1997, two years before Japanese companies overtook U.S. companies in terms of total production of PV cells and modules (see Figure 19).

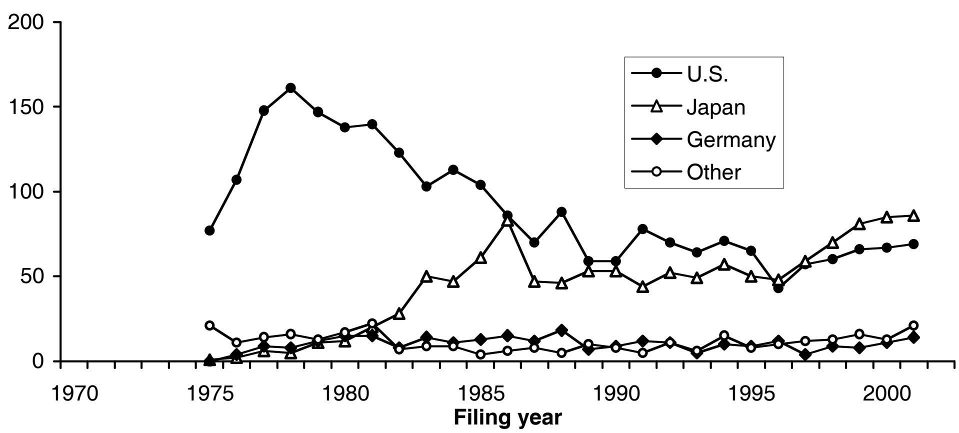

Figure 24. Patents in the class-based PV dataset according to nation of origin and application date, 1976–2001

Figure 25 graphs federal PV R&D funding and patenting activity by U.S. entities (according to inventor nation-of-origin in the class-based PV dataset) over time. Note that although the shapes of the curves are similar, the peak in patenting activity *precedes* the peak in public R&D funding by two years. This counter-intuitive finding should be investigated in later work.

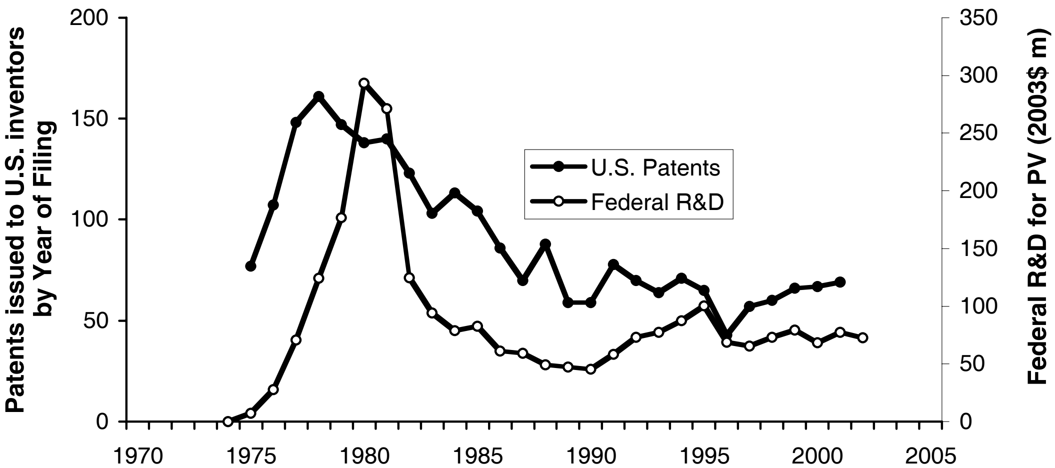

Figure 25. Federal PV R&D funding and patenting activity by U.S. entities, 1974–2002

Finally, Figure 26 shows the number of citations each patent received by other patents. This is an indicator of the importance of a patent to the overall knowledge stock in a technology (the size of the circle in Figure 25 indicates the number of patents at that citation level). Figures like this are expected to exhibit a general decline in citations over time, since later patents have less time to be cited by other patents than earlier patents (it typically takes about ten years for a patent to receive most of its citations). Patents that can be considered "highly cited" in Figure 26 are those that rise highest above the average citations.

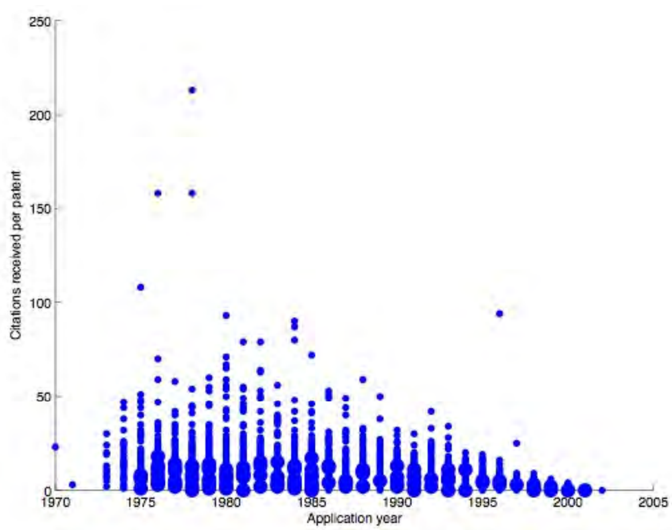

Figure 26. Patents in the PV class-based dataset, by citations received

2.4. Knowledge Transfer Activity

This section focuses on the importance and dynamics of knowledge transfer in PV, as addressed by a graphical and network analysis of PV-relevant technical conferences.

2.4.1. Data

The conference analyzed for this report is the set of (roughly) annual American Solar Energy Society (ASES) conferences. These conferences provided technical papers (in addition to other material) on all three technologies—PV, STE, and SWH—for a long period of time. The first conference included in this dataset was held in 1955 by the pre-cursor to the ASES, the Association for Applied Solar Energy (AFASE); the last was held in 2004.[65] The conference occurred sporadically between 1955 and 1976, when it became an annual event.[66]

Because the papers in the ASES conference address a wide range of "solar" technologies, including the three in this report as well as others, papers in the conference dataset had to be coded for their relevance to PV cell technology. Of the 4,243 papers presented between 1955 and 2004, 22% (920) were coded as PV-relevant papers. Figure 27 displays the number of papers deemed relevant to PV in each year of the ASES conference dataset. Appendix C includes details about the ASES conference dataset and how it was constructed and coded. Dataset details include the locations, dates, and sponsorship of each conference, as well as information on session topics.

[65] AFASE formed in 1954 in Phoenix, Arizona. It was renamed the Solar Energy Society (SES) in 1963 and the International Solar Energy Society (ISES) in 1976.

[66] The conference was then known as the conference of the American Section of the ISES. In 1982, it became known as the conference for the American Solar Energy Society (ASES).

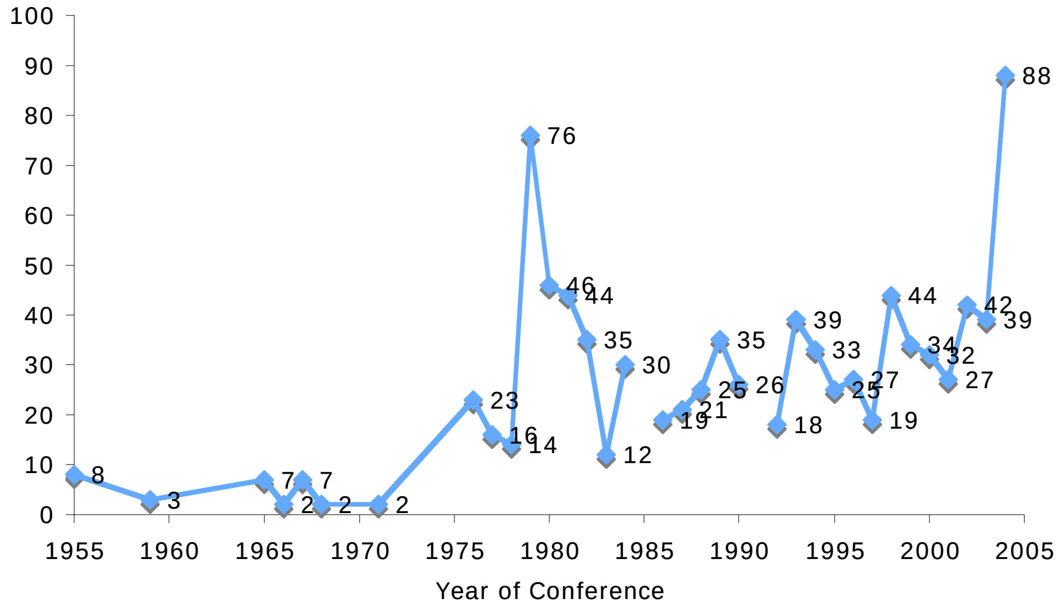

Figure 27. PV-relevant papers in the ASES conference dataset, 1955–2004

2.4.2. Graphical Analysis

In order to appreciate the changing nature of knowledge transfer activity as government actions changed over time, this study divided the conferences in the ASES conference dataset into five periods, based on the expert interviews and the rankings of government actions given in Table 6 in the Government Actions section earlier in this chapter. Table 9 provides these periods, with notes on the context of the times, as well as the conference years included in each period.

Table 9. PV Cell Periods used in Knowledge Transfer Analysis

Period of Knowledge Transfer in PV, w/Context Notes	Conference Years in Period
1: 1955–1973 Solar losing competition w/nuclear power, PV market grows in satellites	1955, 1959, 1965, 1966, 1967, 1968, 1971
2: 1974–1981 Oil crises and emerging interest in terrestrial applications for PV	1976, 1977, 1978, 1979, 1980, 1981
3: 1982–1992 Reagan cuts and R&D stagnation	1982, 1983, 1984, 1986, 1987, 1988, 1989, 1990, 1992
4: 1993–1997 Emerging international markets for terrestrial use	1993, 1994, 1995, 1996, 1997
5: 1998–2004 International market growth, growing state RPS movement stimulates emergent U.S. market	1998, 1999, 2000, 2001, 2002, 2003, 2004

Figure 28 shows the level of activity in the ASES conference dataset according to these periods. “Level of activity” here includes: (1) the number of PV relevant papers (920); (2) the number of authors of these papers (1,258, 83% of whom write papers in only one conference); and (3) the number of organizations with which these authors were affiliated (565).

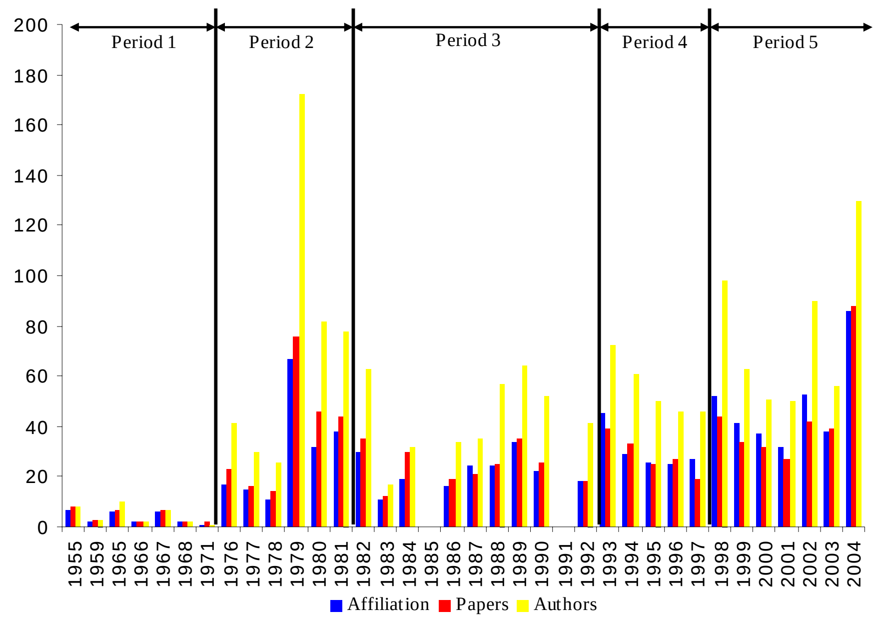

Figure 28. PV-relevant papers, authors, and affiliations in the ASES conference dataset, 1955–2004, according to period

The total number of authors of PV-relevant papers in the ASES conference dataset is, in part, an artifact of the number of authors for each paper over time. Figure 29 displays the coauthorship patterns in the conference dataset for each period. Note that the earliest period, Period 1, has the lowest distribution of the number of authors on a paper across the five periods. For the most part, however, the other four periods exhibit largely the same distribution of papers and number of coauthors, with some outliers.

Authorship of the PV-relevant papers in the ASES conference dataset is attributed to several types of organizations. For this reason, the PV-relevant papers were coded for six types of organizations. “University,” “utility,” “firm” (not utilities), and “government” are self-explanatory organizational types. “Association” represents industry associations, such as ASES itself. “Contract NP R&D” represents contract/nonprofit R&D organizations, such as the utility industry’s R&D consortium, EPRI. Figure 30 shows the results of this coding, with university, non-utility firms, and government the most prominent players in the conference, in order of decreasing importance.

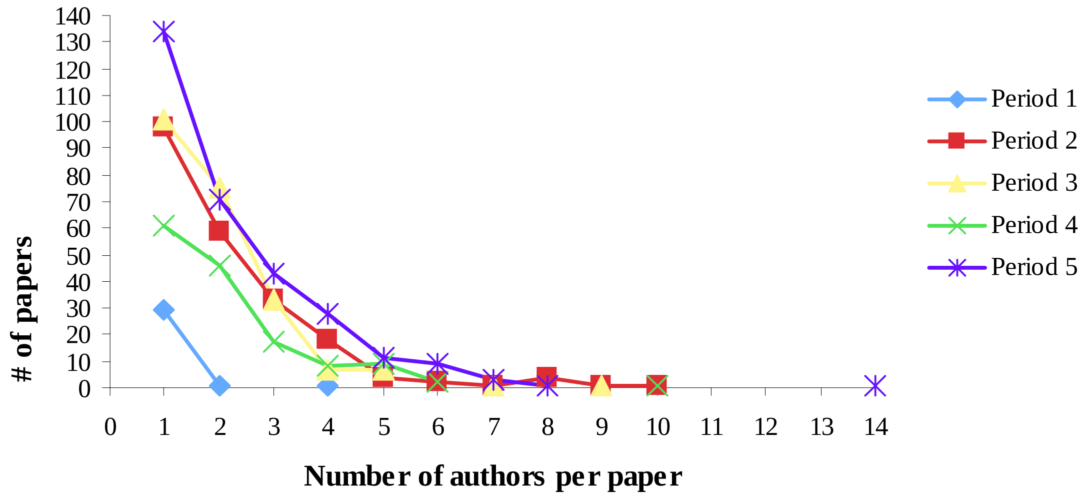

Figure 29. Coauthorship patterns in PV-relevant papers in the ASES conference dataset, 1955–2004, according to time period

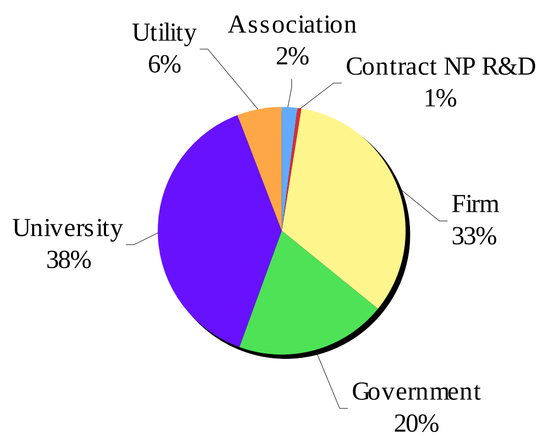

Figure 30. PV-relevant papers in the ASES conference dataset, 1955–2004, by type of affiliate organization

Finally, Figure 31 shows how the authorship of PV-relevant papers in the ASES conference dataset breaks down by geographic origin. The United States dominates the conference, with 89% of the total authorship, including the 13% attributed to California alone.[67] Note that the foreign-authored proportion of the papers (11%) is mainly comprised by Canada (15%), Spain (12%), and Mexico (7%). This is somewhat surprising, considering the strength of Japan and Germany as market leaders for PV.

[67] This presumably mirrors the American sponsorship of the conference.

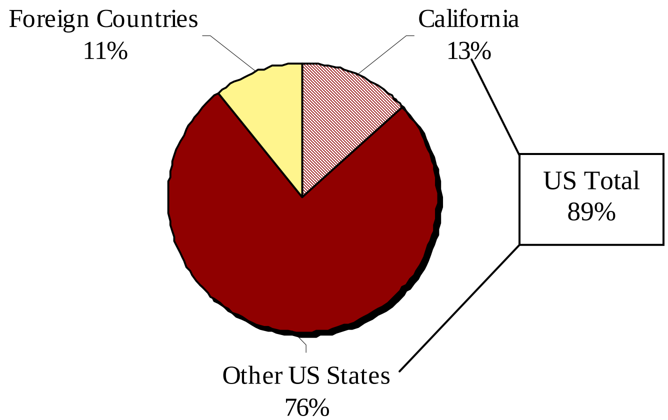

Figure 31. PV-relevant papers in the ASES conference dataset, 1955–2004, by geographic origin

2.4.3. Network Analysis

The individuals and organizations coauthoring papers in the ASES conference form a technical communication network that can be analyzed using computational techniques developed in sociology. The basic relational data to be analyzed are the *ties* between the 1,258 authors of the PV-relevant papers in the ASES conference dataset. In this case, a tie is a relationship between two authors. As an example, a paper with three authors—A, B, and C—has three distinct ties between them: A-to-B, B-to-C, and A-to-C. These ties can be of two types—*reflexive* and *relational*—and can vary along a few different dimensions. For example, if A and B are from the same type of organization, they are characterized as having a reflexive affiliation-type or organization-type tie. It is possible, however, that A and B are from the same type of organization but different individual organizations; in such a case, the organizational tie between them would be considered relational.

Ties can also vary based on their strength. In this analysis, a tie (or coauthor relationship) is considered *strong* if it accounts for 10% or more of the total ties in a period; a tie is considered *regular* if it accounts for between 2 and 9% of the ties in a period; and a tie is considered *weak* if it accounts for 1% or less of the total ties in a period.

Table 10 presents the strong and regular ties among affiliation types, by period, according to coauthorship of PV-relevant papers in the ASES conference dataset. Although the proportion of weak ties in a given period is listed in the header row in Table 10, weak ties are otherwise excluded from the analyses that follow. Note that the six affiliation types in the table—firms, utility, university, contract nonprofit R&D, trade association and government—are the same as in the graphical analysis above.

Table 10. Strong and regular affiliation-type ties among authors of PV-relevant papers in the ASES conference dataset, 1955–2004, according to period

Period 1 (1955–1973) 31 Papers 7 Ties, 0% Weak		Period 2 (1974–1981) 219 Papers 550 Ties, 3% Weak		Period 3 (1982–1992) 221 Papers 340 Ties, 2% Weak		Period 4 (1993–1997) 143 Papers 323 Ties, 1% Weak		Period 5 (1998–2004) 306 Papers 743 Ties, 1% Weak	
Univ Reflex	86%	Univ Reflex	46%	Univ Reflex	38%	Univ Reflex	26%	Univ Reflex	24%
Util Reflex	14%	Firm Reflex	20%	Firm Reflex	25%	Gov Reflex	19%	Firm Reflex	23%
		Gov Reflex	12%	Gov Reflex	16%	Firm Reflex	18%	Firm-Univ	14%
		Firm-Univ	8%	Firm-Univ	8%	Firm-Gov	13%	Firm-Gov	11%
		Gov-Univ	3%	Util Reflex	3%	Firm-Util	7%	Gov-Univ	10%
		Cntrct Reflex	3%	Firm-Util	3%	Gov-Univ	4%	Gov Reflex	5%
		Cntrct -Univ	2%	Firm-Gov	2%	Univ-Util	4%	Firm-Util	4%
		Firm-Gov	2%	Gov-Univ	2%	Util Reflex	3%	Assoc Reflex	3%
		Firm-Util	1%			Firm-Univ	2%	Assoc-Firm	3%
						Assoc-Gov	2%	Util Reflex	1%
						Gov-Util	1%	Assoc-Univ	1%

It is clear from Table 10 that the earliest conferences in the ASES dataset did not exhibit significant coauthorship. Of the thirty-one papers presented in Period 1 of the conference, only seven ties occurred. Six were amongst authors from universities, and one was between authors from utilities, making all seven ties reflexive. But coauthorship grew, and no other period exhibits a greater number of papers than ties. Table 10 points out that total ties were at their highest in Period 5 (743 ties for 306 papers), the period in which markets for grid-connected PV are particularly high. The second highest ties occurred in Period 2, the hopeful solar era when public R&D levels for solar energy technologies were quite high. Period 4 and 5 display the most diverse cross-affiliation type ties of the five periods (in terms of the number of affiliation-type ties exhibited in Table 10), with Period 2 the next most diverse.

As illustrated in Figure 32, all of the ties in Period 1 were reflexive; this indicates that the papers presented to the ASES conference in that period exhibited no direct research contribution from the diverse approaches and perspectives represented by cross-affiliation type relational ties. By Period 2, the era of high R&D budgets and the public pursuit of multiple solar energy technologies, relational ties were up to almost 40% of all ties. By Period 3, as resources and popular support for solar declined, reflexive ties were back to around 80% of all ties. Period 4, which shows an emerging international market for PV, and Period 5, which shows a strengthening U.S. and international market, show successive increases in the proportion of relational ties in the ASES conference.

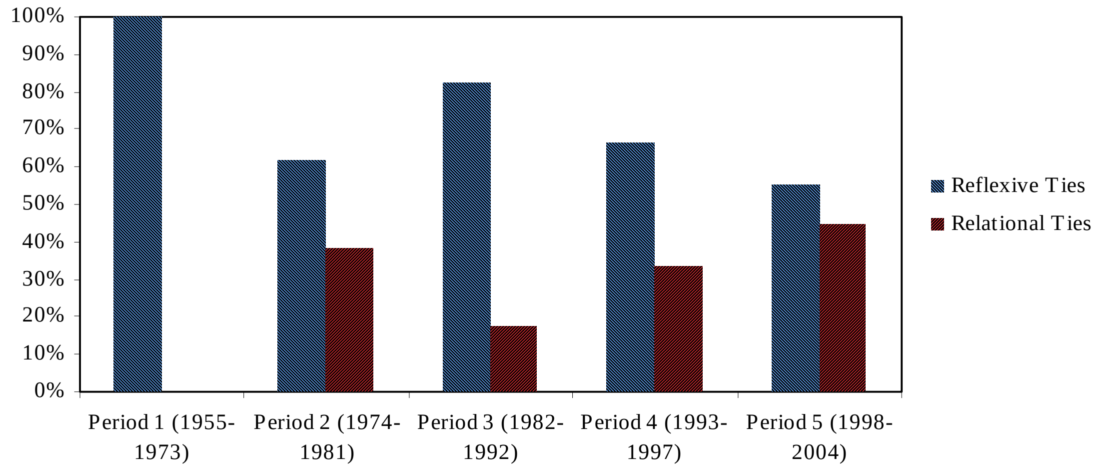

Figure 32. Reflexive and relational affiliation-type ties among authors of PV-relevant papers in the ASES conference dataset, 1955–2004, according to period

Figure 33 illustrates the shifting prominence of particular affiliation types in coauthoring PV-relevant papers at the ASES conference, according to each type's share of strong and regular ties (either on both sides or only one side of a tie) in different time periods. Period 1 is almost entirely dominated by university researchers, but that share declines by Period 2, reaching its lowest amount by Period 4; even in Period 4, however, universities were the largest influence on coauthorship ties in the PV-relevant ASES conference papers. Government and non-utility firms also account for a large number of ties in the ASES dataset. Although neither had any prominence in Period 1 (1955–1973), both were significant actors in the PV-relevant papers in the ASES conference by Period 2, with government accounting for its highest proportion of ties in Period 4 (1993–1997)[68] and non-utility firms showing their highest proportion in Period 5 (1998–2004).[69]

[68] The Clinton-era "Million Solar Roofs" initiative seems a likely candidate (for investigation in later work) to explain this prominence in 1993–1997.

[69] The emerging market for off-grid small PV systems, both domestically and internationally, is a likely candidate (for investigation in later work) to explain this prominence in 1998–2004.

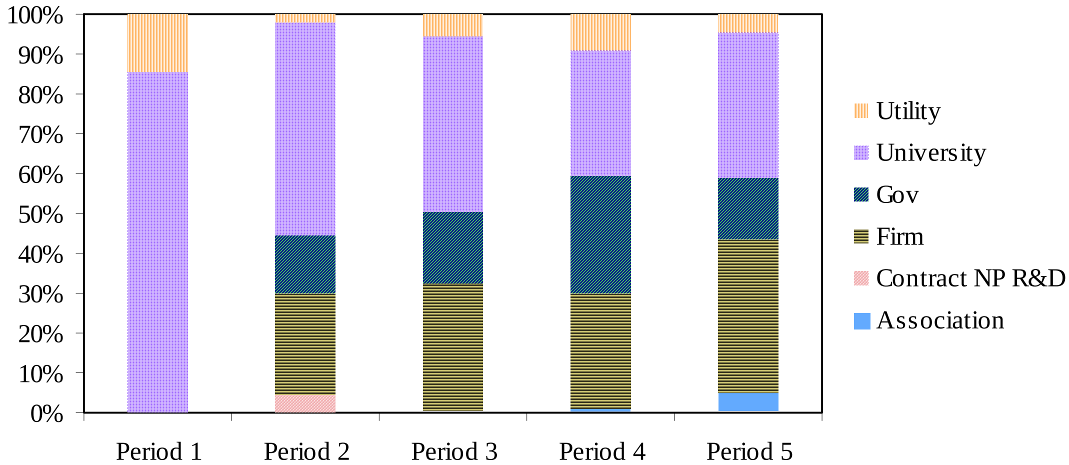

Figure 33. Strong and regular affiliation-type ties on PV-relevant papers in the ASES conference dataset, 1955–2004, according to period

2.5. Experience Curves

Quantitative modeling of "experience curves" has become an increasingly common method of representing endogenous technical change in long-term integrated assessment models used for energy and environmental policy analysis. This section focuses on quantifying the outcomes of innovation in PV cells by developing experience curves, which relate improvements in the cost or performance of a technology to the cumulative production of that technology. Experience curves are based on an organizational learning curve, the classical formula for which is given below.[70]

$$y_i = a x_i^{-b}$$

where:

y = the number of labor hours required to produce the ith unit
a = the number of labor hours required to produce the first unit
x = the cumulative number of units produced through time period i
b = the learning rate
i = a time subscript

The x-variable in this equation is a proxy for knowledge acquired through production. It is computed by summing the total units of output produced from the start of production up to, but not including, the current year (this is because of the standard assumption that experience acquired over the course of a given year will not be reflected in technical improvements in the year the experience is gained). In the PV case, the "output" considered is the cumulative megawatts of electrical capacity (MW) produced. Because available *y*-variable data is given with reference to both PV *modules* and PV *systems*, the x-variables in the experience curves in this section will differ based on the corresponding y-variables of interest. Figure 34 illustrates the data underlying the x-variable of the

[70] For a comprehensive review of organizational learning curves, see Argote (1999).

cumulative capacity of PV *modules* over time, while Figure 35 illustrates the data underlying the x-variable of the cumulative capacity of PV *systems* over time. Figure 35 also illustrates worldwide system prices over time.

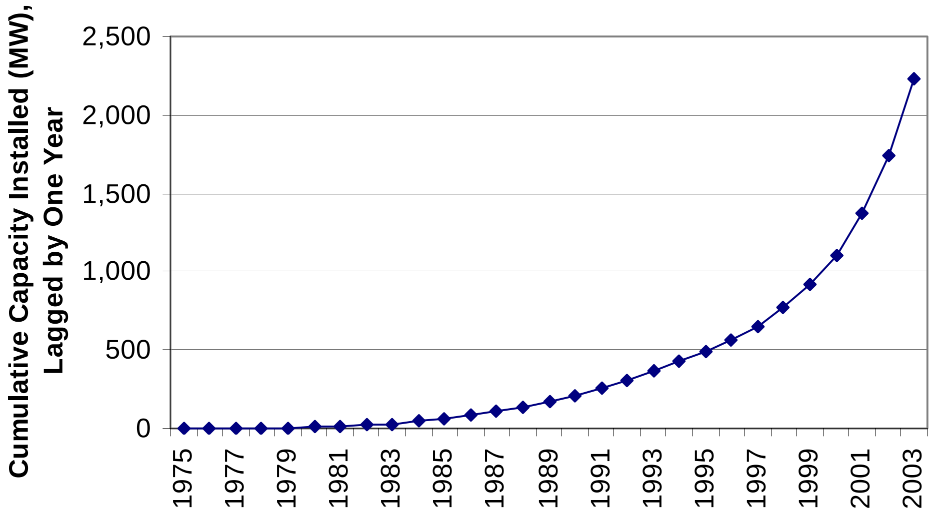

Figure 34. Cumulative capacity of PV modules installed (MW)

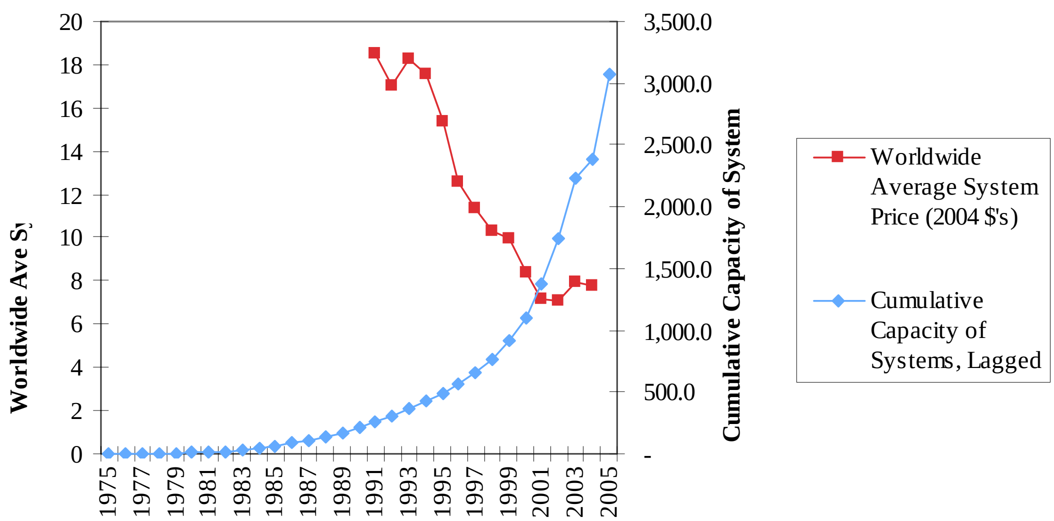

Figure 35. Cumulative capacity of PV systems installed (MW)

The y-variable in the experience curve equation is represented by three attributes in this section: module capital costs, module efficiency (a performance metric), and system costs for full systems. Prices are used as the measure of costs, and are given in constant 2004 dollars. Figure 36, Figure 37, and Figure 38 depict the experience curves—on a log-log scale—regarding the price and efficiency of PV modules and/or systems as cumulative capacity (lagged by one year) increases. The main sources used in constructing these figures are: Maycock and Bower (2004); Nowak (2004); Schaeffer, Seebregts et al. (2004); and CEC (2005).

Figure 36 is an experience curve of the average PV module cost in $/peak-Watt, according to an average of two world surveys of PV prices. The line shown is the best-fit of a power function relating the x- and y-variables; at 0.99, the goodness-of-fit is strong. The parameter b (-0.37) in the equation—the learning rate—translates into a progress ratio of $2^{-0.37}$, or 0.77.[71] This means that as cumulative output doubles, the PV module cost declines to 77% of its original level, which is slightly better than the most frequently observed progress ratio in such industries as electronics, machine tools, papermaking, aircraft, steel, and automobiles, which is 80% (Dutton and Thomas 1984).

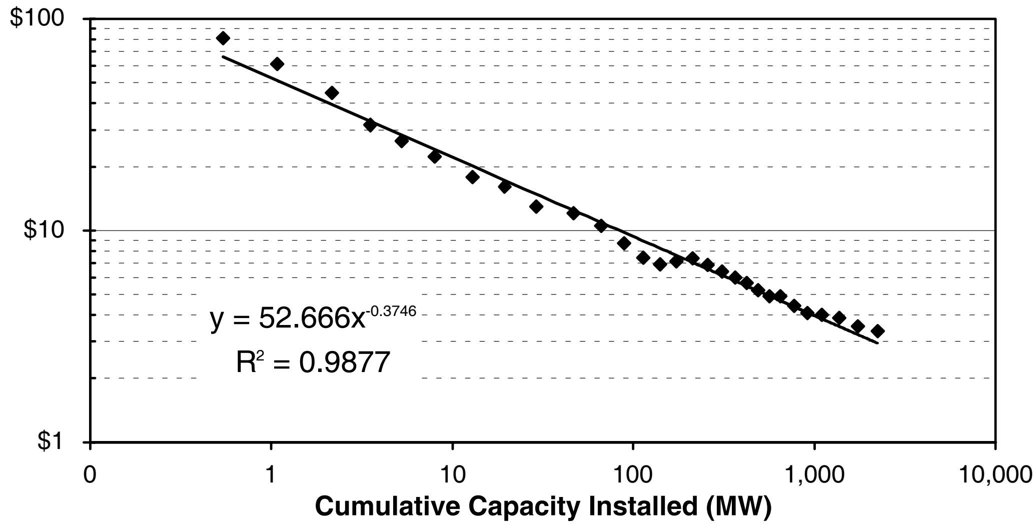

Figure 36. Experience curve for the capital cost of PV modules, as measured in prices

Figure 37 is an experience curve of the average efficiency of commercial modules. The best-fit line shown, a power function relating the x- and y-variables, has a strong goodness-of-fit at 0.99. The line is positive, reflecting efficiency improvements that have accrued with experience, and relatively flat. The parameter b (0.10) in the equation—the learning rate—translates into a progress ratio of 1.07. This means that as cumulative output doubles, PV module efficiencies reach 107% of their original levels.

[71] All numbers derived from equations in Figure 36, Figure 37, and Figure 38 are presented in the text of this section to the second decimal point.

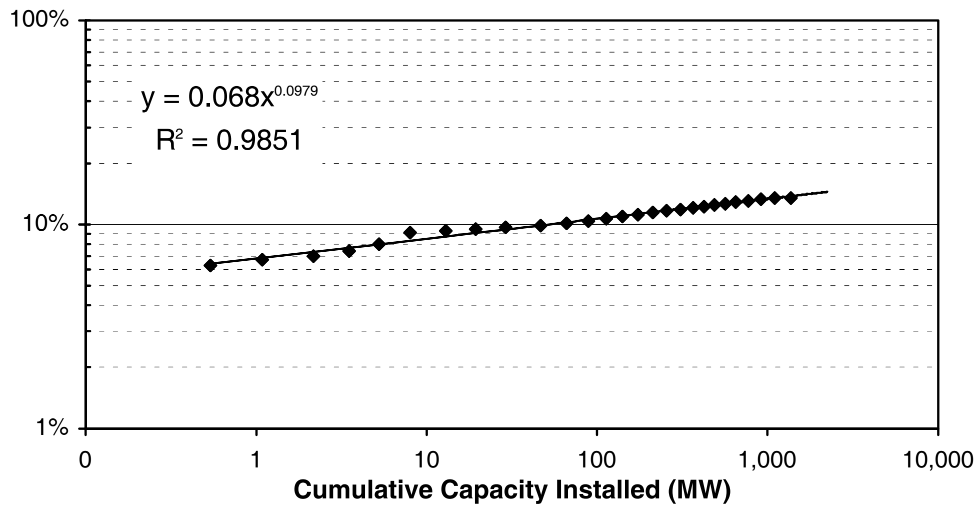

Figure 37. Experience curve for the efficiency of commercial PV modules

Figure 38 is an experience curve of the cost of PV *systems*. This metric of technological improvement is more comprehensive than the earlier module cost metric, as it includes such balance-of-system costs as inverters and junction boxes, as well as the cost of installation. Unfortunately, the data for system costs do not reach as far back in time as the data for module costs. The best-fit line shown in Figure 38, a power function relating the x- and y-variables, is not as strong a fit as the other two PV figures, at 0.88. The parameter b (-0.45) in the equation—the learning rate—translates into a progress ratio of $2^{-0.45}$, or 0.73. This means that as cumulative output doubles, PV system costs decline to 73% of their original levels, which is better than the frequently seen progress ratio of 80%.

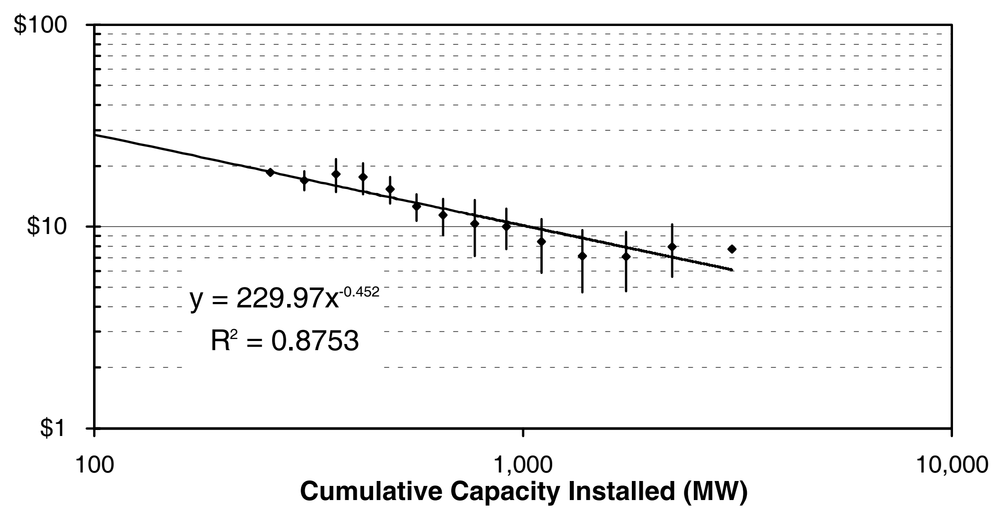

Figure 38. Experience curve for the cost of PV systems, as measured in prices

3.0 Solar Thermal Electric Power

This chapter focuses on the role of government actions on innovation in solar thermal electric (STE) technology. The chapter includes: (1) an overview of the technology, including major developments; (2) an assessment of inventive activity and its relationship to government actions, as addressed through analysis of patenting activity; and (3) a consideration of the importance and dynamics of knowledge transfer in the development of STE, as addressed by expert interviews and a graphical and network analysis of conferences pertinent to the technology. Following this treatment of the innovation process and its relationship to government actions, the chapter concludes with a treatment of the outcomes of innovation, as measured through experience curves relating technological diffusion to performance and cost improvements.

3.1. Technology Overview

All technologies that convert incoming solar radiation into thermal energy, either for use directly as heat or for conversion into electricity, as in the case of STE, are considered "solar thermal" technologies (Larson and West 1996). Since the 1970s, the federal government has applied four categories to solar thermal technologies: "(1) active solar heating and cooling; (2) passive solar heating and cooling; (3) industrial process heat; and (4) solar thermal electricity" (ibid., p. 4).[72] This chapter focuses on STE technologies, while the next chapter focuses on "residential active solar thermal hot water systems" which provide domestic water heating (ibid. p. 5).[73]

Solar Thermal Electric technologies typically use a system of mirrors to concentrate solar radiation onto an absorber that converts the radiation to heat (about 400°C) and transfers that heat to a fluid which can then be used to generate electricity "by means of Rankine, Brayton, or Stirling thermal cycles" (Grosskreutz 1996). Figure 39 provides a simple schematic of a generic STE unit and its connection to the electrical grid.

Today, the three "most promising architectures" for STE are: (1) parabolic troughs; (2) central receivers; and (3) parabolic dishes (Mariyappan and Anderson 2001). These architectures are named on the basis of the shape of their collectors. For example, Figure 39 depicts a parabolic trough architecture, so called because the "solar collector field" in the figure—which contains the mirrors and the absorber—is shaped like a parabolic trough.

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[72] Most federal solar commercialization efforts "through the early 1980s were directed at the four solar thermal areas because they were perceived to be nearest to commercial viability" (Larson and West 1996, p. 4).

[73] The term "active" implies a pump that circulates a fluid (usually water or water plus antifreeze when the panel is warm enough" (Larson and West 1996, p. 6). Although some passive solar water heating systems—which employ little to no "mechanical or electrical energy to move fluids"—they are a small segment of the market (ibid.).

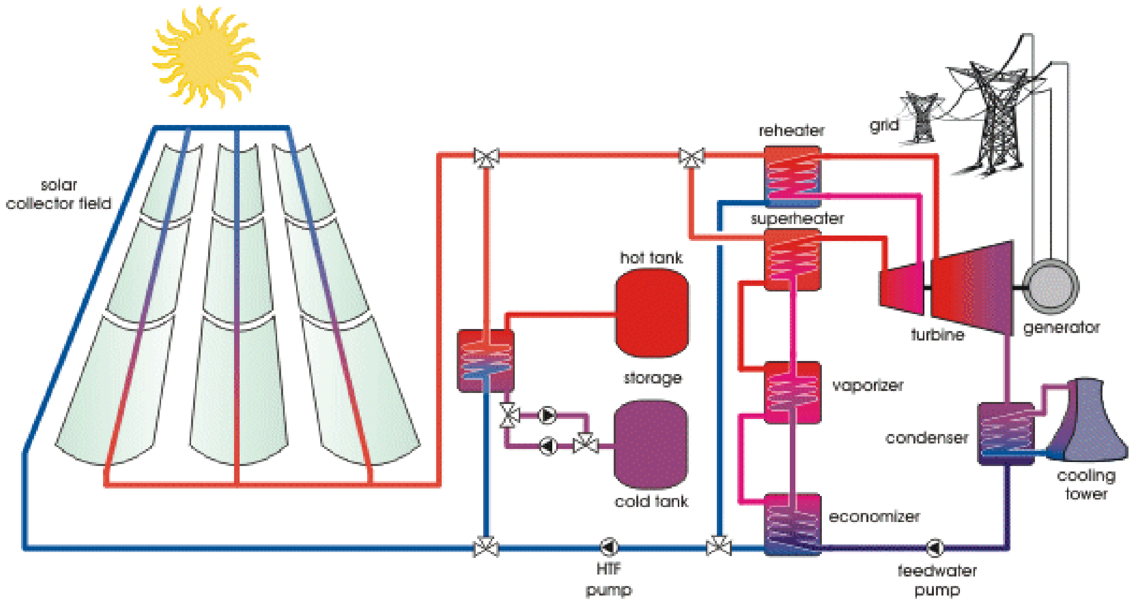

Figure 39. Schematic of a generic STE unit

Source: (Tester, Drake et al. 2005)

(1) *Parabolic troughs:* These systems, the only STE architecture in commercial use until the early 2000s, use an array of mirrors shaped as parabolic troughs to "concentrate sunlight onto thermally efficient receiver tubes placed at the trough focal point" (Mariyappan and Anderson 2001). These absorption tubes pump a heat transfer fluid, typically oil, after it is heated to approximately 400 degrees centigrade. The heated fluid flows "through heat exchangers to produce superheated steam" which "is converted to electric energy in a conventional turbine generator (e.g., Rankine-cycle/steam turbine) or a combined cycle (gas turbine with bottoming steam turbine)" (ibid.). Additional components which may be present in some systems include: a natural gas burner that can be used to produce steam in low- or no-sun conditions, cooling systems, and storage for the heated fluid. Figure 40 illustrates a simplified parabolic trough design.

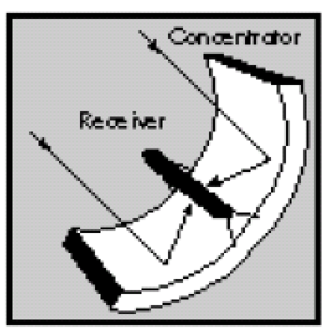

Figure 40. Diagram of a parabolic trough STE architecture

Source: (Mariyappan and Anderson 2001)

(2) *Central receivers:* These systems, which have not been commercially deployed in the United States, use a circular array of "heliostats," or large, individually sun-tracking mirrors, to reflect and concentrate solar radiation onto a central receiver mounted on a tower (Mariyappan and Anderson 2001; Brakmann, Aringhoff et al. 2005).[74] The central receiver "absorbs the energy reflected by the concentrator and by means of a heat exchanger (e.g., air/water) produces superheated steam" (Mariyappan and Anderson 2001). Alternatively, a working fluid (typically molten nitrate salt) is pumped through tubes in the receiver, "heated to approximately 560 degrees centigrade, and pumped either to a 'hot' tank for storage or through heat exchangers to produce superheated steam" which is converted to electricity in much the same fashion as in parabolic trough systems. Note that central receivers can be distinguished by their high temperatures and by their use of daily storage for the heated fluid, which is possible because of the short distance the fluids flow. Figure 41 depicts a simplified central receiver system.

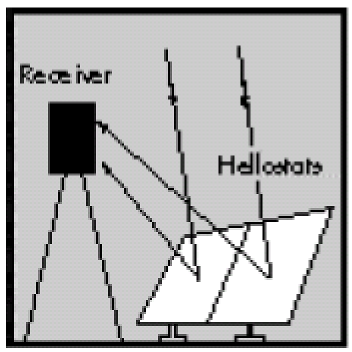

Figure 41. Diagram of a central receiver STE architecture

Source: (Mariyappan and Anderson 2001)

(3) *Parabolic dishes:* These systems, which are not in commercial use, use an array of mirrors shaped as parabolic dishes "to concentrate sunlight onto a receiver located at the focal point of the dish" (Mariyappan and Anderson 2001). The receiver "absorbs energy reflected by the concentrators, and fluid in the receiver is heated to approximately 750 degrees Centigrade" (ibid.). The very hot fluid is then "used to generate electricity in a small engine (e.g., Stirling or Brayton cycle) attached to the receiver" (ibid.). Note that parabolic dish systems are typically smaller, free-standing STE units (~25kW) (Brakmann, Aringhoff, et al. 2005). Figure 42 illustrates a simplified parabolic dish system.

[74] This configuration is the root of the term "power towers," which is also used in reference to central receiver systems.

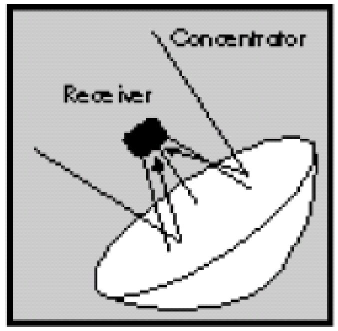

Figure 42. Diagram of a parabolic dish STE architecture

Source: (Mariyappan and Anderson 2001)

Each of these STE architectures has its own advantages and disadvantages, some of which are shown in Table 11.

Table 11. Characteristics of the three main STE architectures

	Parabolic Trough	Central Receiver	Parabolic Dish
Applications	Grid-connected plants; process heat; (Highest solar capacity to date: 80 MWe)	Grid-connected plants; high temperature process heat; (Highest solar capacity to date:10 Mwe)	Stand-alone applications or small off-grid power (Highest solar system capacity to date: 25 kWe)
Advantages	Commercially available (over 9 billion kWh operational experience, with solar collection efficiency up to 60%, peak solar-to-electrical conversion of 21%); hybrid concept proven; storage capability	Good mid-term prospective for high conversion efficiencies solar collection efficiency approx.46% at temps up to 565°C, peak solar-to-electrical conversion of 23%); storage at high temperatures; hybrid operation possible	Very high conversion efficiencies (peak solar-to-electrical conversion of about 30%); modularity; hybrid operation; operational experience
Disadvantages	Lower temperatures (up to restrict output to moderate steam qualities due to temperature limits of oil medium	Capital cost projections not yet proven	Low efficiency combustion in hybrid systems and reliability yet to be proven

Source: (Mariyappan and Anderson 2001)

Although the earliest known work on STE technologies is attributed to Augustin Mouchot in the 1870s, when he used "cone-shaped, solar concentrators to drive simple heat engines," the first major commercial application of STE did not occur until the early 1900s and 1910s, with "Aubrey Eneas' first commercial solar motors and Frank Shuman's 45kW sun-tracking parabolic trough plant built in Meadi, Egypt" (Grosskreutz 1996; Mariyappan and Anderson 2001). When the energy crises occurred in the 1970s, STE projects based on the early commercial designs were "undertaken in a number of industrialized nations, including the United States, Russia, Japan, Spain, and Italy" (ibid.).

Besides parabolic trough designs, the U.S. government also invested in central receiver facilities. Table 12 shows the capital cost improvements seen in central receiver STE facilities in the 1980s. Note that some of these demonstration plants were victims of Reagan-era budget cuts; as one expert put it, "Solar One people went to NASA in order to survive." The real commercial success in STE, however, was the nine parabolic trough "solar electric generating stations" (SEGS) built by Luz International, Inc. between 1984 and 1991 in California's Mojave Desert. Until Luz went bankrupt in 1991, the SEGS plants were the most successful STE commercialization effort in the world; they remained so until late 2005.

Table 12. Trends in central receiver STE capital costs, 1981–1987

Plant	Size (MWe)	Cost Basis	Direct Capital Cost ($1987/kWe)	Heliostat Cost ($1987/ft^2)	Direct Capital Cost less Heliostat Cost ($1997/kWe)
Solar One (water/steam) SAN 86-8002	10	As constructed, 1981	10,800	60	6,228
Solar 100 (salt) MMC	100	As bid, 1982, MMC	4,216	31	2,602
Solar 100 (salt) MDAC	100	As bid, 1982, MDAC	4,110	26	2,813
Saguaro stand-alone (salt)	58	Preliminary design, 1983	3,963	36	1,054
EPRI TAG (water/steam hybrid)	152	Bechtel study, 1984	2,769	20	1,824
APS utility study (salt)	100	Conceptual design, 1987	2,516	9	1,638
APS utility study (salt)	200	Conceptual design, 1987	1,959	7	1,238

Source: (Grosskreutz 1996)

The U.S. government has been tracking data on solar collector manufacturing in "shipments" data going back to 1984. Table 13 compiles much of the data regarding STE shipments over time.[75] Note that low- and medium-temperature solar collectors are discussed in the SWH chapter. Some of the government data on these other collectors has relevance to STE, although the vast majority of collectors are not high-temperature.

[75] STE shipments are contained in the term "high-temperature solar collectors," which indicates collectors that generally operate at temperatures above 180 degrees Fahrenheit. All three of the architectures described here—parabolic trough, central receiver, and parabolic dish—operate at these temperatures.

Table 13. Shipments of high-temperature solar collectors in the United States, 1984–2004

Year	Quantity Shipped	Price ($/ft^2)
1984	773	Not Applicable
1985	Not Applicable	“
1986	4,498	“
1987	3,155	“
1988	4,116	“
1989	5,209	17.76
1990	5,237	15.74
1991	1	31.94
1992	2	75.66
1993	12	22.12
1994	2	177
1995	13	53.26
1996	10	18.75
1997	7	25
1998	21	53.21
1999	4	286.49
2000	5	Value withheld to avoid disclosure of proprietary data
2001	2	“
2002	2	“
2003	7	“
2004^{P}	0	0

Source: (EIA 2006b, Table 10-3).
P indicates that the data is preliminary.

The dramatic increase in STE shipments between 1984 and 1990 and their subsequent severe decline starting in 1991 is directly tied to the construction of the SEGS units. In those same years, Luz achieved significant cost improvements as well as increased the size, performance, and efficiency of STE plants.[76] As shown in Figure 43, the SEGS plants (with assistance from Sandia National Laboratories) drove “the levelized cost of electricity down from a reported 24 U.S.¢/kWh to 8¢/kWh” (Mariyappan and Anderson 2001). Although the SEGS plants clearly benefited from federal and state tax credits as well as “attractive power purchase contracts,” they were also the recipients of some $1.2 billion from private risk capital and institutional investors (ibid.).

[76] The SEGS plants “ranged from 14 to 80 MWe unit capacities and totaled 354 MWof grid electricity” (Mariyappan and Anderson 2001).

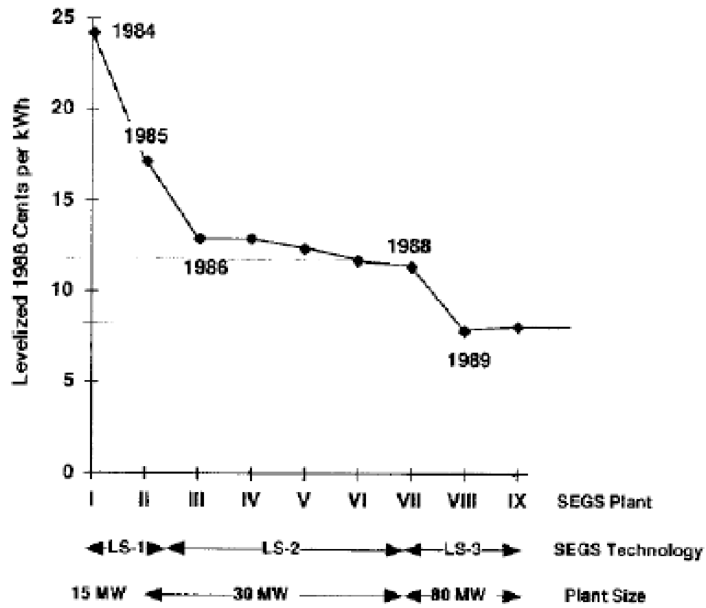

Figure 43. Levelized costs in SEGS units constructed over time

Source: (Lotker 1991)

Figure 44 depicts cumulative installed capacity of commercial STE technology in the United States; all of this capacity can be attributed to the SEGS plants. Note that the SEGS plants are still in "profitable commercial operation with a history of increased efficiency and output as operators improved their procedures," despite the fact that no new plants have been built since 1990 (ibid). Between 1992 and 1997, five of the 30 MW SEGS plants "averaged 105 percent of rated capacity during the four-month summer on-peak period (12 noon-6pm, weekdays)" and achieved "a 37% reduction in operation and maintenance (O&M) costs" (ibid.). In addition, the SEGS plants overall "achieved a highest annual plant efficiency of 14% and a peak solar-to-electrical efficiency of about 21%" (ibid.).

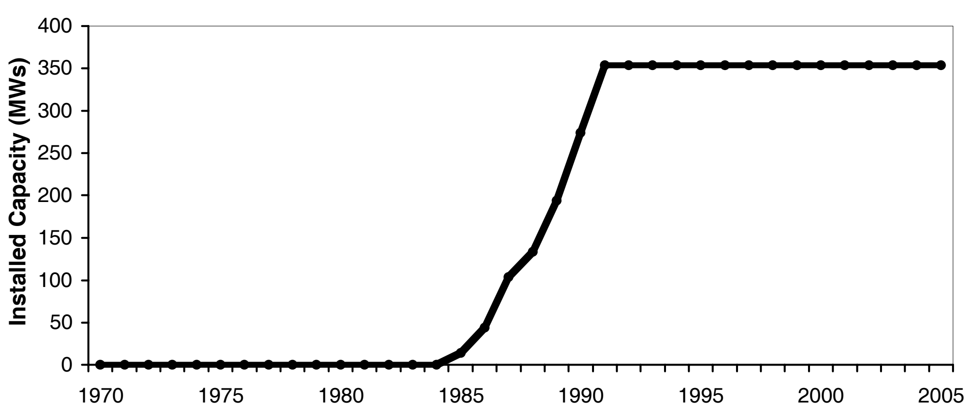

Figure 44. Cumulative installed capacity of commercial STE systems (parabolic trough architectures) in the U.S., 1970–2005

Source: (Kearney and Price 2005)

The success of STE technology, including its favorable cost standing as opposed to PV cells, raises the question of why there have been so few units built since the demise of Luz in 1991. In the United States, at least, the explanation for this lies in the deregulation of the electricity sector. According to some industry observers, uncertainty related to deregulation "has lowered the depreciation times for capital investments in new plant capacity" (Mariyappan and Anderson 2001). Highly efficient "natural gas-fired combined cycle gas turbine plants" have proven to be intense competition for STE; they take "approximately two years to build" and their capital costs are "still declining below $500/kW with generation efficiencies of over 50%" (ibid). To be competitive, STE facilities have to be quite large, requiring large capital investments "deemed too high a risk by financiers" (ibid.).[77]

Important innovations have occurred in STE technologies since the 1970s, both before and after the demise of Luz. These innovations have occurred primarily in three technical areas: (1) heliostats; (2) field configuration; and (3) steam reheating.

1. *Heliostats:* The development of heliostats, the largest component of capital cost in new plants, made construction of the first commercial units possible. Key improvements in heliostat development have included better optical transmission of sunlight to the receiver, lighter weight, and greater resistance to wind and storms (Lotker 1991).

2. *Field configuration:* Improvements have been made in configuring solar arrays to maximize heating (in combination with steam reheating) and significantly boost system efficiency (Kearney and Price 2005).

3. *Steam reheating*: The introduction of steam reheating into turbine design has increased STE efficiency significantly (specifically, the efficiency of the Rankine cycle). The basic principle behind steam reheating is that high-temperature steam is reheated after it leaves the turbine through use of the working fluid; it then returns to the turbine (IEA 2005).

3.2. Government Actions

The complexity of the solar policy history presented in the introduction to this report, which is in part due to the fact that many of the policy instruments designed to promote solar over the years applied to more than one solar technology, prompted an appeal to experts to sort through the relative importance of various government actions on technological innovation in STE.[78] Table 14 and Figure 45 compile the responses of the experts interviewed for this report on this issue. Experts ranked government actions on a

[77] Note that before it went bankrupt, Luz officials were calling for a 130 MW plant, and up to 300 MW plants in later years, in order to capture economies of scale (Mariyappan and Anderson 2001).

[78] Appendix B details the procedure with which experts where selected, as well as the interview methodology and protocol.

scale of 1-5, with 5 having the most important effect (negative or positive) on the industry and the development of the technology.

Table 14. Expert opinion of importance of government actions to innovation in STE

Government Action	Expert A	Expert B	Expert C	Expert D	Expert E	Expert F[79]	Expert G	Average Score (Scale 1–5, with 5 most important)
1981–85 Standard offer contracts for PURPA, (~11¢/kWh)	5	5	4	5	5			4.8
1978 Public Utilities Regulatory Policy Act (PURPA)	5	5	3	4.5	5			4.5
2004 Spain 12¢/kWh above market price for STE	5	3	4	5	4			4.2
1997–present 21 other state RPSs and 3 solar set-asides	4	2	4	5	4			3.8
1974–2005 United States Federal STE R&D	3	3	4	5	2			3.4
1977–86 CA energy business tax credit (25%)	5	1			3.5			3.2
1974–2005 EU STE R&D		3	5	2	2.5			3.1
2002 CA RPS		4		1	4			3.0
1978–present Solar Business Energy Tax Credit (10%)	4		2	2	3.5			2.9
2004 Renewable Energy Production Tax Credit (1.9¢/kWh)	4	2	3	1	4			2.8
1974 Japan “Sunshine Project” (STE R&D)	2	2	4	5	1			2.8
1998–present CEC and CPUC “buydown” rebate programs	5	1		1	1			2.0
1990 Germany electricity feed law (similar to PURPA)	1	1	2	5	1			2.0
1978–85 Residential energy tax credits (25% incr. to 40%)	5	1	1	1	1			1.8
mid-1990s state regulatory changes e.g., net metering	1	0	1		2			1.0

[79] While Experts F and G were interviewed, they declined to provide rankings of the policies.

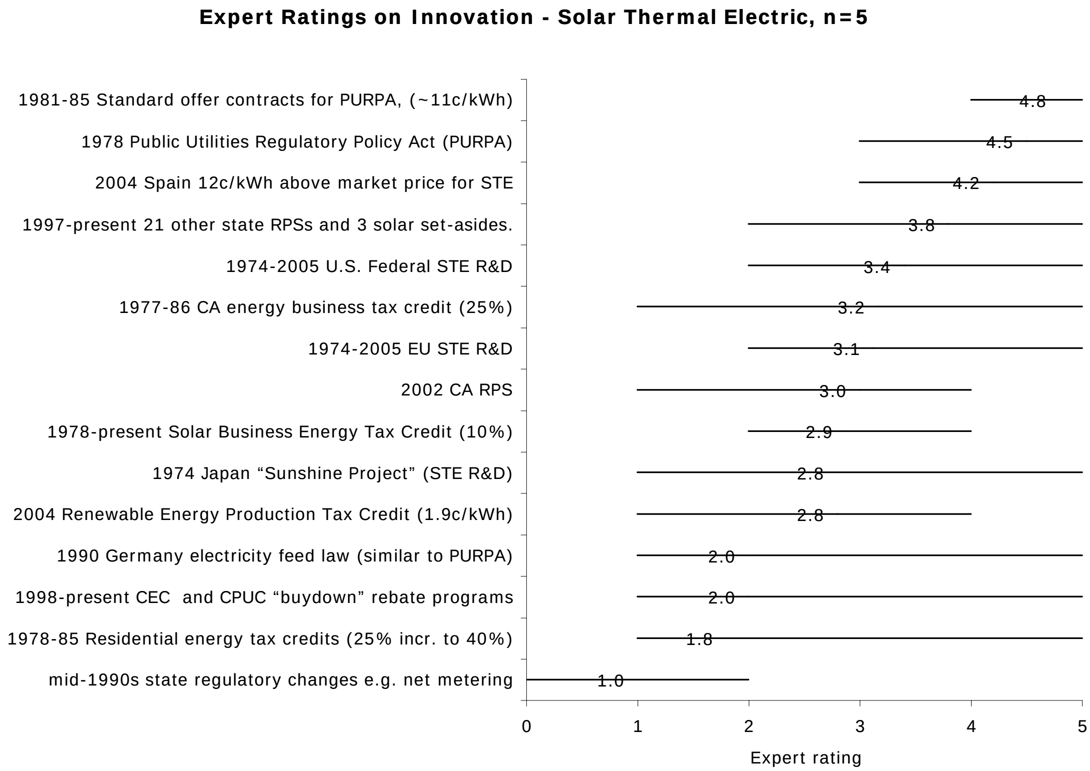

Figure 45. Expert ratings of policies relevant to STE

3.3. Inventive Activity

Two metrics are often used in the economics of innovation literature to give insight into inventive activity: R&D funding is used as an input metric, while patents are used as an output metric. This section will only treat the analysis of patenting activity in STE, as the introduction chapter to this report discusses various solar energy R&D programs in the United States, California, Germany, and Japan. Figure 1, Figure 3, Figure 4, Figure 6, and Figure 7 all contain national solar energy R&D data.[80]

As outlined in the introduction to this report, two patent datasets—a "class-based" dataset and an "abstract-based" dataset—were created for this analysis using two different approaches to manipulating patent data. Details on the construction of these datasets can be found in Appendix A and in Section 1.3.1 of this report.

Inventors have different reasons for filing (or not filing) patents, depending on their perception of the economic value of patents in their industry. In any technology-based industry targeted for patent analysis, it is important to try to understand this perception in order to place the results of analysis in context. In the STE industry, the experts interviewed for this analysis felt that patents were not as representative of major innovations in STE as were patents in SWH technologies. They justified this, in part, by

[80] Preliminary work shows that California's solar energy R&D is not insignificant, although it has proven to be too difficult to compile into a comprehensive time-series in time for the publication of this report.

explaining that Luz, the major commercial STE firm mentioned above "had very few patents on what they were doing." Experts also explained that the important innovations in STE were based on "standard engineering" and hypothesized that "maybe the universe of potential patents has been exhausted."

3.3.1. Datasets

The class-based dataset of STE patents netted 537 patents granted between 1858 and 2002. Figure 46 portrays this dataset according to the patent application date, which is the earliest date that can be consistently tied to the inventions that are granted patents. As there is generally a two-year lag between the patent application date and the date the patent is granted, the dataset in Figure 46 ends in 2002 (as do most of the patent figures in this report). Note that this dataset is not "clean," as patents in this figure were not coded for relevance to STE.

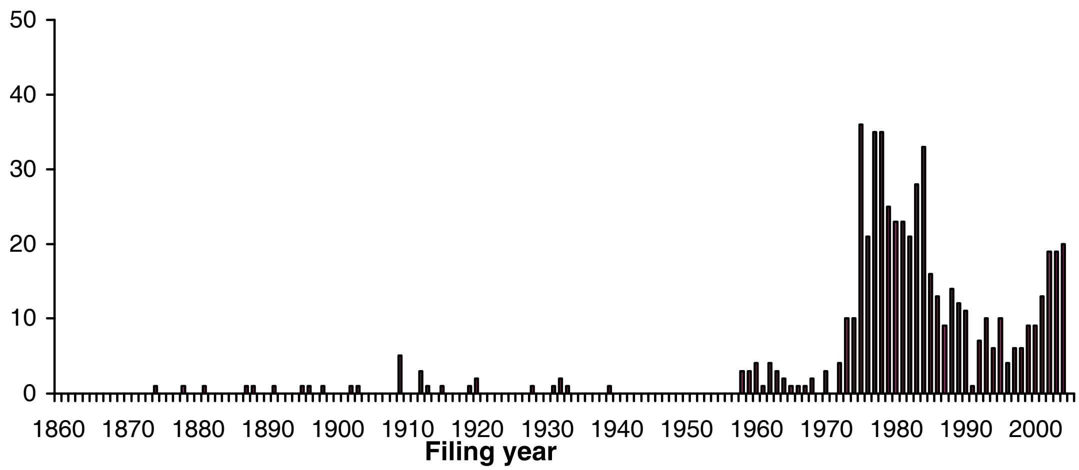

Figure 46. Class-Based Dataset of STE Patents, by Application Date, 1858–2002

Although the class-based dataset is consistent for over 100 years, and thus, can be used to relate patenting trends to the timing of long-past government actions related to the technology, the tradeoff for the length of this dataset is that it is less certain with respect to under-counting and over-counting than are other approaches to patent analysis. As in the other technology cases in this report, an "abstract-based" was created to complement the class-based dataset and in part.

The abstract-based approach to creating a patent dataset for STE netted 601 patents granted between 1975 and 2002. Figure 47 shows the abstract-based patent dataset for STE, according to the patent application date. Note that this dataset is "clean," as patents in this figure were coded for relevance to STE. The coding of the abstract-based dataset, and initial samples of the class-based dataset, indicate that the coded abstract-based dataset is a more reliable patent dataset to understand STE technology. For this reason, analyses in this STE chapter—unlike the previous PV chapter—are based on the "clean" abstract-based dataset.

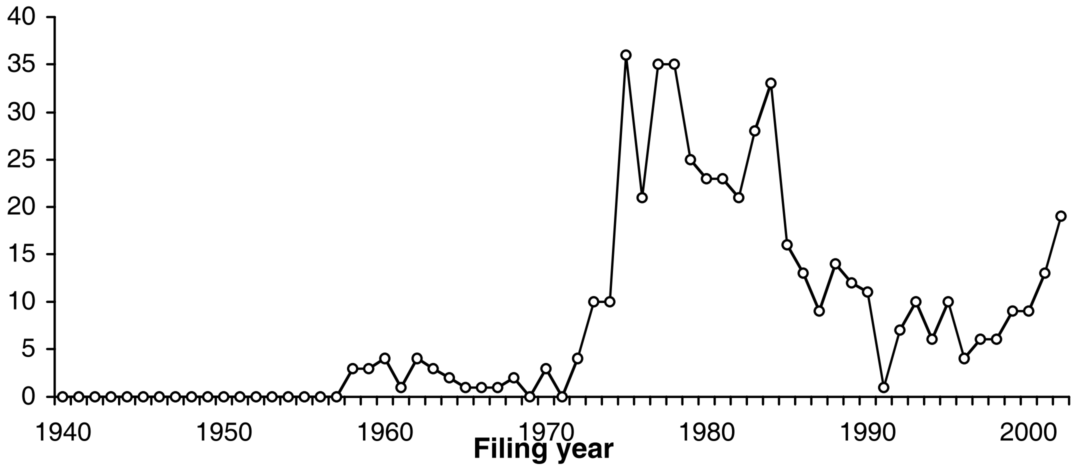

Figure 47. “Clean” abstract-based dataset of STE patents, by application date, 1940–2002

Like the class-based dataset, the “clean” abstract-based patent dataset shows that overall STE patenting activity has a peak in the late-1970s, then drops off only to rebound in the late 1990s and early 2000s.

3.3.2. Descriptive Statistics

Table 15 shows the top ten patent holders in the “clean” STE abstract-based patent dataset. Note that, unlike in the PV case, the most significant patent holder in STE is the U.S. government. This is an interesting distinction, since both technologies received significant public R&D subsidies.

Table 15. Top ten patent holders in the “clean” STE abstract-based patent dataset

Patent Owner	Country	Number of Patents	% of Total
The United States of America	United States	14	4.6
The Boeing Company	United States	9	3.0
UOP Inc.	United States	7	2.3
Hughes Aircraft Company	United States	7	2.3
Rockwell International Corporation	United States	6	2.0
Canon Kabushiki Kaisha	Japan	6	2.0
Owens-Illinois, Inc.	United States	5	1.6
Deutsches Zentrum fuer Luft- und Raumfahrt e.V.	Germany	5	1.6
Solmat Systems, Ltd.	United States	5	1.6
Ormat Industries Ltd.	United States	5	1.6
		Total	**22.6**

Table 15 also makes it clear that intellectual leadership in STE technology, according to the percentage of patenting activity controlled by the top-ten patent holders (22.6%), is much less concentrated than in PV cells (56.9%). This intellectual leadership is much less international than in the case of PV cells: eight of the patent owners in Table 15 are American, one is Japanese, and one is German.[81] The most prominent U.S. companies in this table are in the aerospace sector, which received a considerable amount of the "big solar" R&D dollars in the late 1970s (the period that corresponds with the highest patenting activity in the STE abstract-based dataset), much to the chagrin of solar "soft path" advocates. Note that Luz, the most significant actor in terms of installed STE capacity, is not a major patent holder, which seems to match expert perceptions of patenting in STE technology.

Table 16 provides a more comprehensive sense of patent ownership in the "clean" STE abstract-based patent dataset. The percentage of patents held by the top ten patent holders identified in Table 15 (22.6%) is included in Table 16 for purposes of comparison to the percentage of patents held by individuals (50.6%) and California-based inventors (22.9%).

Table 16. Patent ownership in the "clean" STE abstract-based patent dataset

Patent Ownership	Proportion in STE Abstract-Based Dataset (%)
Top 10 Assignees	22.6
Individuals	50.6
California Inventors	22.9

Figure 48 shows all patenting activity in the "clean" abstract-based STE patent dataset between 1974 and 2002, according to the inventor nation-of-origin. Patenting activity in the United States increased dramatically in the mid-1970s, peaking in 1976 and then leveling off through 1979. Patenting activity then declined rapidly in the early 1980s to reach its lowest level in 1983. From 1984 on, levels stayed more or less the same at about a quarter of peak levels. Other countries do not seem to patent significantly in this technology in the U.S. system; this is likely to be an effect of the lack of a U.S. market for STE technologies.

[81] The prominent Japanese company patent owner is also the most prominent patent owner in PV technologies, as seen in
Table 7. The German organization is the German Aerospace Center, which is run as a chartered nonprofit organization.

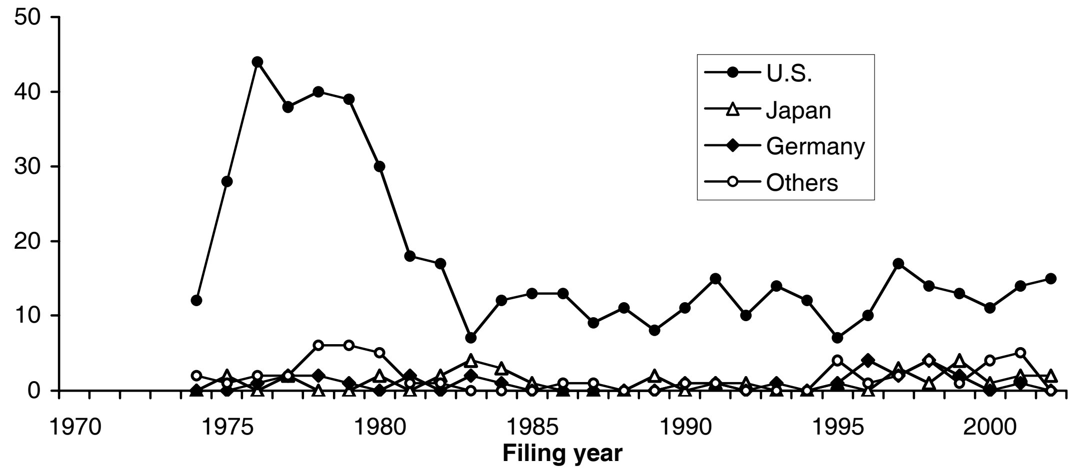

Figure 48. Patents in the "clean" abstract-based STE patent dataset according to nation of origin and application date, 1974–2002

Figure 49 graphs federal STE R&D funding and patenting activity by U.S. entities (according to inventor nation-of-origin in the "clean" abstract-based patent dataset) over time. Note that although the shapes of the curves are similar, the peak in patenting activity *precedes* the peak in public R&D funding by four years. This counter-intuitive finding should be investigated in later work.

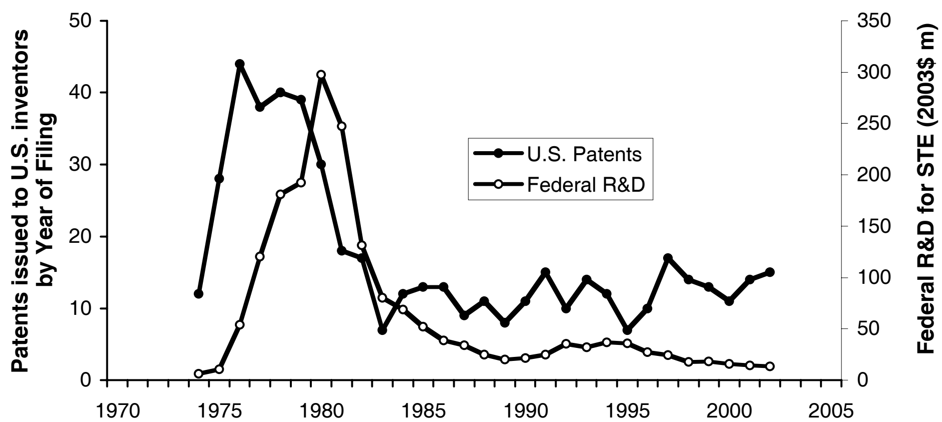

Figure 49. Federal STE R&D funding and patenting activity by U.S. entities, 1974–2002

Finally, Figure 50 shows the number of citations each patent in the "clean" abstract-based STE dataset received by other patents. This is an indicator of the importance of a patent to the overall knowledge stock in a technology (the size of the circle in Figure 50 indicates the number of patents at that citation level). Figures like this are expected to exhibit a general decline in citations over time, since later patents have less time to be cited by other patents than earlier patents (it typically takes about ten years for a patent to receive most of its citations). Patents that can be considered "highly cited" in Figure 50 are those that rise highest above the average citations.

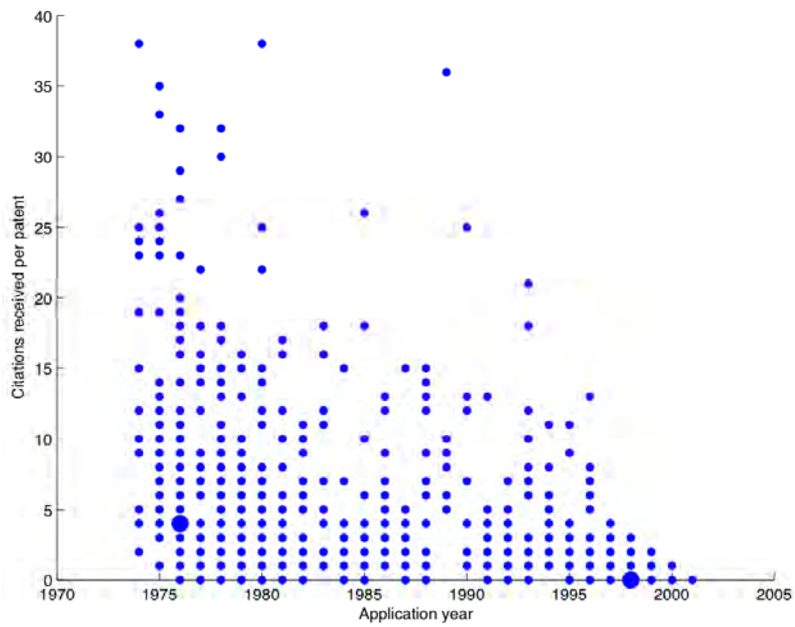

Figure 50. Patents in the "clean" STE abstract-based dataset, by citations received

3.4. Knowledge Transfer Activity

This section focuses on the importance and dynamics of knowledge transfer in STE, as addressed by a graphical and network analysis of STE-relevant technical conferences.

3.4.1. Data

The conference analyzed for this report is the set of (roughly) annual ASES conferences. These conferences provided technical papers (in addition to other material) on all three technologies—PV, STE, and SWH—for a long period of time. The first conference included in this dataset was held in 1955 by the pre-cursor to the ASES, the AFASE; the last was held in 2004.[82] The conference occurred sporadically between 1955 and 1976, when it became an annual event.[83]

Because the papers in the ASES conference address a wide range of "solar" technologies, including the three in this report as well as others, papers in the conference dataset had to be coded for their relevance to STE technology. Of the 4,243 papers presented between 1955 and 2004, 12% (508) were coded as STE-relevant papers. Figure 51 displays the number of papers deemed relevant to STE in each year of the ASES conference dataset. Appendix C includes details about the ASES conference dataset and how it was

[82] AFASE formed in 1954 in Phoenix, Arizona. It was renamed the Solar Energy Society (SES) in 1963 and ISES in 1976.

[83] The conference was then known as the conference of the American Section of the ISES. In 1982, it became known as the conference for the ASES.

constructed and coded. Dataset details include the locations, dates, and sponsorship of each conference, as well as information on session topics.

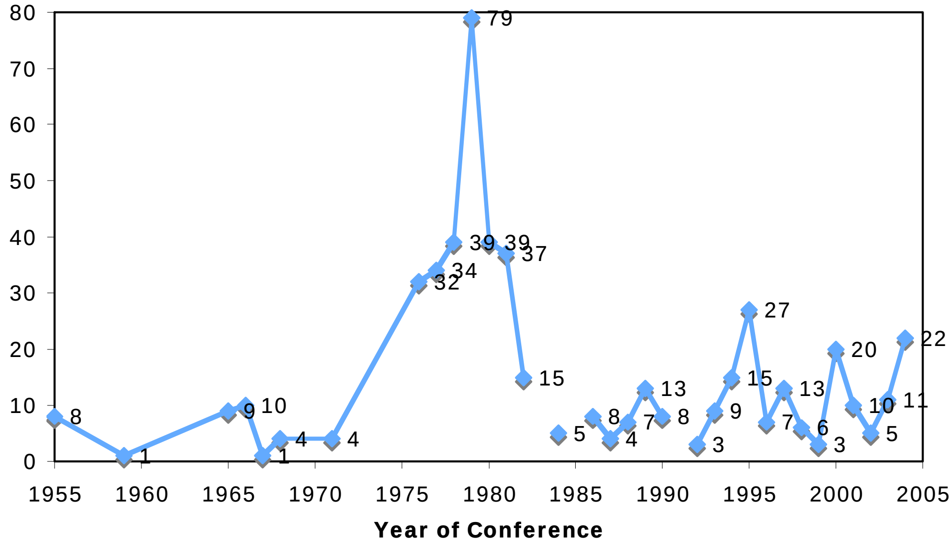

Figure 51. STE-relevant papers in the ASES conference dataset, 1955–2004

3.4.2. Graphical Analysis

In order to appreciate the changing nature of knowledge transfer activity as government actions changed over time, this study divided the conferences in the ASES conference dataset into five periods, based on the expert interviews and the rankings of government actions given in Table 14 in the Government Actions section earlier in this chapter. Table 17 provides these periods, with notes on the context of the times, as well as the conference years included in each period.

Table 17. STE technology periods used in knowledge transfer analysis

Period of Knowledge Transfer in STE, w/Context Notes	Conference Years in Period
1: 1955–1973 Solar losing competition w/nuclear power	1955, 1959, 1965, 1966, 1967, 1968, 1971
2: 1974–1981 Oil crises and government support for solar thermal applications like STE	1976, 1977, 1978, 1979, 1980, 1981
3: 1982–1992 Era of SEGS plants	1982, 1983, 1984, 1986, 1987, 1988, 1989, 1990, 1992
4: 1993–1997 Commercial market collapses	1993, 1994, 1995, 1996, 1997
5: 1998–2004 Emerging international market, growing state RPS movement stimulates emergent U.S. market	1998, 1999, 2000, 2001, 2002, 2003, 2004

Figure 52 shows the level of activity in the ASES conference dataset according to these periods. “Level of activity” here includes: (1) the number of STE relevant papers (508); (2) the number of authors of these papers (795, 85% of whom write papers in only one conference); and (3) the number of organizations these authors were affiliated with (299).

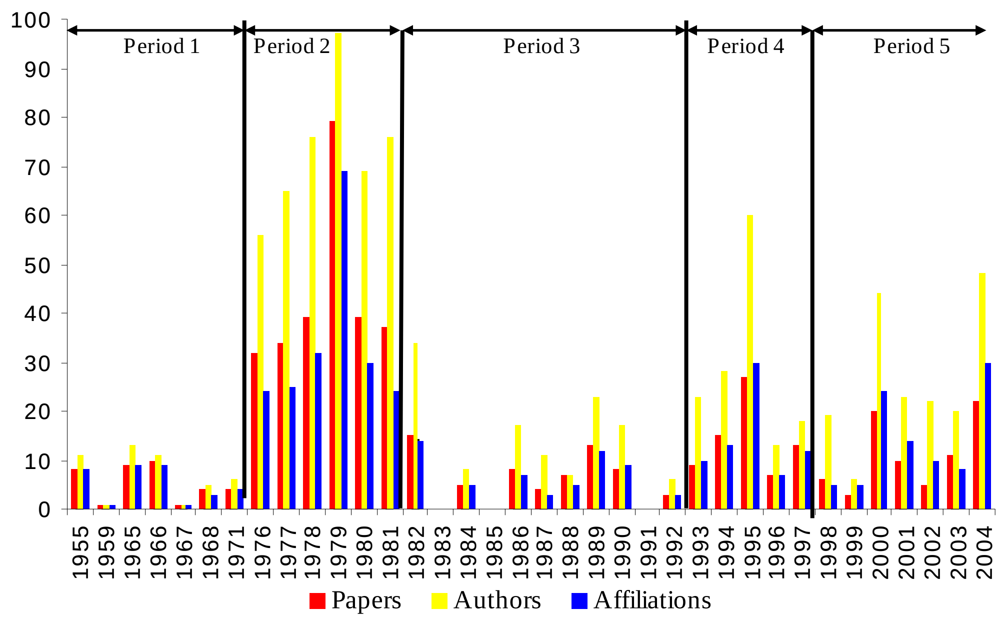

Figure 52. STE-relevant papers, authors, and affiliations in the ASES conference dataset, 1955–2004, according to time period

The total number of authors of STE-relevant papers in the ASES conference dataset is, in part, an artifact of the number of authors for each paper over time. Figure 53 displays the coauthorship patterns in the conference dataset for each period. Note that the earliest period, Period 1, has the lowest distribution of the number of authors on a paper across the five periods. For the most part, however, the other four periods exhibit largely the same distribution of papers and number of coauthors, with some outliers.

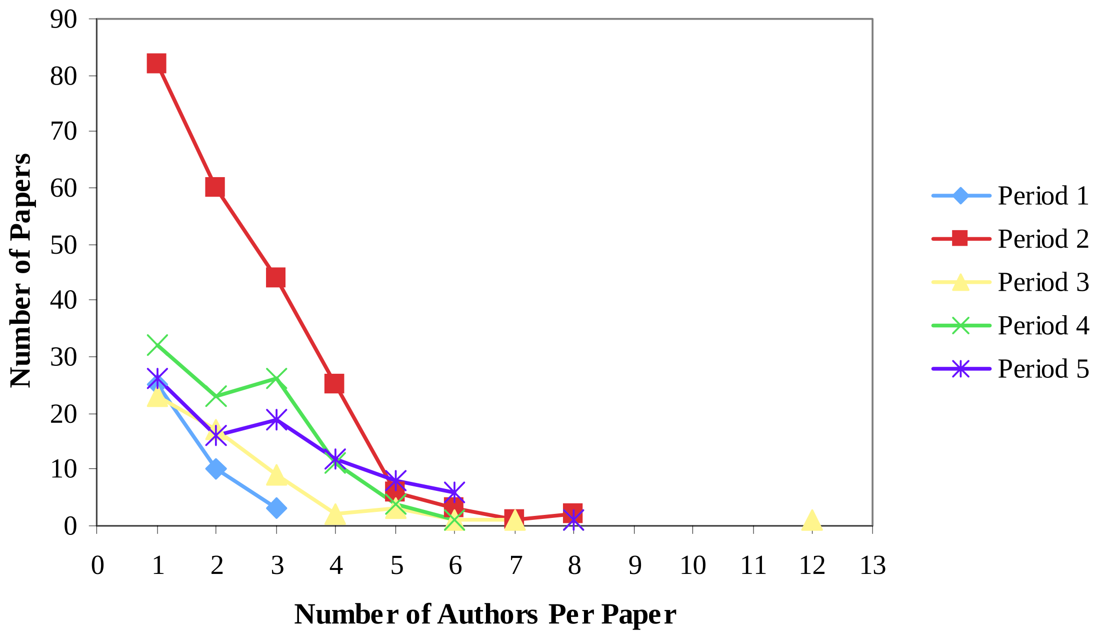

Figure 53. Coauthorship patterns in STE-relevant papers in the ASES conference dataset, 1955–2004, according to time period

Authorship of the STE-relevant papers in the ASES conference dataset is attributed to several types of organizations. For this reason, the STE-relevant papers were coded for six types of organizations. “University,” “utility,” “firm” (not utilities), and “government” are self-explanatory organizational types. “Association” represents industry associations, such as ASES itself. “Contract NP R&D” represents contract/nonprofit R&D organizations, such as the utility industry’s R&D consortium, EPRI. Figure 30 shows the results of this coding, with university, non-utility firms, and government the most prominent players in the conference, in order of decreasing importance.

Figure 54 shows how the authorship of the STE-relevant papers in the ASES conference breaks down by the types of organizations the authors represent. This gives a gauge of how active the various aspects of the STE industrial-environmental innovation complex have been in the technical dialogue on STE that has been sponsored by government for so many years. Universities author 42% of the papers, firms author 30% of the papers, and government authors 24% of the papers The other three affiliation types (utility, association, contract nonprofit R&D) make minimal contributions to the conference.

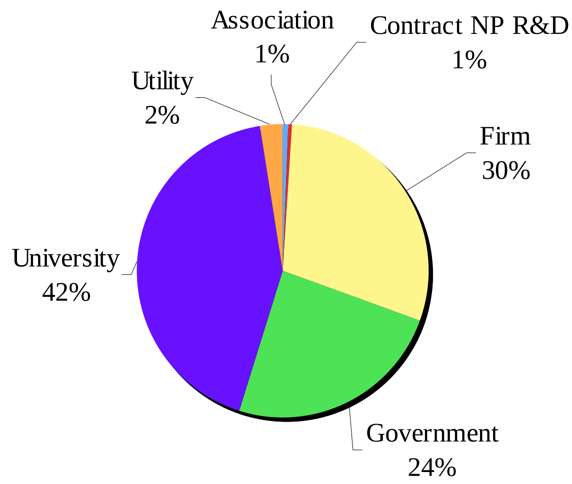

Figure 54. STE-relevant papers in the ASES conference dataset, 1955–2004, by type of affiliate organization

Finally, Figure 55 shows how the authorship of STE-relevant papers in the ASES conference dataset breaks down by geographic origin. The United States dominates the conference, with 82% of the total authorship, including the 17% attributed to California alone.[84] Note that the foreign-authored proportion of the papers (18%) is mainly comprised by France (17%), Japan (12%), and Mexico and Italy at 10% each.

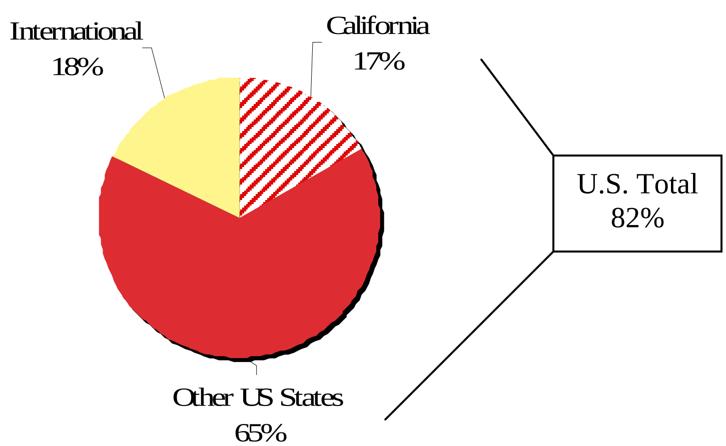

Figure 55. STE-Relevant Papers in the ASES Conference Dataset, 1955–2004, by Geographic Origin

[84] This presumably mirrors the American sponsorship of the conference.

3.4.3. Network Analysis

The individuals and organizations coauthoring papers in the ASES conference form a technical communication network that can be analyzed using computational techniques developed in sociology. The basic relational data to be analyzed are the *ties* between the 795 authors of the STE-relevant papers in the ASES conference dataset. In this case, a tie is a relationship between two authors. As an example, a paper with three authors—A, B, and C—has three distinct ties between them: A-to-B, B-to-C, and A-to-C. These ties can be of two types—*reflexive* and *relational*—and can vary along a few different dimensions. For example, if A and B are from the same type of organization, they are characterized as having a reflexive affiliation-type or organization-type tie. It is possible, however, that A and B are from the same type of organization but different individual organizations; in such a case, the organizational tie between them would be considered relational.

Ties can also vary based on their strength. In this analysis, a tie (or coauthor relationship) is considered *strong* if it accounts for 10% or more of the total ties in a period; a tie is considered *regular* if it accounts for between 2% and 9% of the ties in a period; and a tie is considered *weak* if it accounts for 1% or less of the total ties in a period. Table 18 presents the strong and regular ties among affiliation types, by period, according to coauthorship of PV-relevant papers in the ASES conference dataset. Although the proportion of weak ties in a given period is listed in the header row in Table 18, weak ties are otherwise excluded from the analyses that follow. Note that the six affiliation types in the table—firms, utility, university, contract nonprofit R&D, trade association and government—are the same as in the graphical analysis above.

Table 18. Strong and regular affiliation-type ties among authors of STE-relevant papers in the ASES conference dataset, 1955–2004, according to period

Period 1 (1955–1973) 37 Papers 18 Ties, 0% Weak		**Period 2 (1974–1981) 260 Papers 523 Ties, 0% Weak**		**Period 3 (1982–1992) 60 Papers 188 Ties, 1% Weak**		**Period 4 (1993–1997) 74 Papers 255 Ties, 2% Weak**		**Period 5 (1998–2004) 77 Papers 341 Ties, 1% Weak**	
Firm Reflex	33%	Univ Reflex	37%	Univ Reflex	54%	Univ Reflex	49%	Univ Reflex	39%
Gov Reflex	22%	Firm Reflex	23%	Firm Reflex	18%	Gov-Univ	18%	Firm Reflex	18%
Univ Reflex	22%	Gov Reflex	19%	Gov Reflex	18%	Firm Reflex	14%	Firm-Univ	11%
Firm-Gov	17%	Gov-Univ	5%	Firm-Univ	6%	Gov Reflex	11%	Gov Reflex	8%
Univ-Gov	6%	Firm-Gov	5%	Cntrct Reflex	2%	Firm-Univ	4%	Gov-Firm	8%
		Cntrct -Univ	4%	Gov-Univ	2%	Firm-Gov	3%	Gov-Univ	6%
		Firm-Univ	3%	Util Reflex	1%			Gov-Util	3%
		Firm-Util	3%					Firm-Util	3%
		Util Reflex	2%					Assoc-Firm	1%
								Univ-Util	1%
								Cntrct Reflex	1%

It is clear from Table 18 that the earliest conferences in the ASES dataset did not exhibit significant coauthorship. Of the thirty-seven papers presented in Period 1 of the conference, only eighteen ties occurred. All but four were reflexive—that is, non-utility firm authors coauthoring with other authors from non-utility firms, government authors coauthoring with other authors from government, and university authors coauthoring with other authors from universities. But coauthorship grew, and no other period exhibits a greater number of papers than ties. Table 18 points out that total ties were at their highest in Period 2 (523 ties for 260 papers), the hopeful solar era when many approaches were being attempted and public R&D levels were high. In Period 3, by contrast, when the commercial market for STE became established in the SEGS plants, the number of papers and ties both declined, although at different rates (papers declined by a factor of 4.3 while ties declined by a factor of 2.8). Papers and ties both increased in Period 4 and Period 5. Period 5 is also noteworthy for displaying the most diverse set of cross-affiliation type ties of the five periods in terms of the number of affiliation-type ties exhibited in Table 18. Period 2 is the next most diverse.

As illustrated in Figure 56, most (78%) of the ties in Period 1 were reflexive; this indicates the papers presented to the ASES conference in that period exhibited little direct research contribution from the diverse approaches and perspectives represented by cross-affiliation type relational ties. Relational ties shrank even further in the second (19%) and third (10%) periods. This is counter-intuitive, as the market for STE was growing in these periods, and Period 3, in particular, is a period of documented innovation as the SEGS plants were built and the size, performance, and efficiency of parabolic trough STE facilities improved. One explanation is that the ASES conference was not the forum for the presentation of the results of these efforts; this would also help explain the low number of papers in Period 3. Indeed, this is supported in the expert interviews for this report; one expert explained "industry guys rarely publish, [they are] worried about stolen ideas." On the other hand, relational ties (as well as papers and total ties) grow in Period 4, which was also a period of documented innovation in the SEGS facilities. As stated in the Technology Overview above, between 1992 and 1997 the existing SEGS plants increased their generating efficiency (five of the nine to an average of 105% of rated capacity during summer peak hours), lowered their O&M costs (those same plants achieved a 37% reduction), and, as will be shown in the Experience Curve section below, became increasingly reliable (the number of pump failures, in particular, declined). Further work will be required to resolve some of these discrepancies.

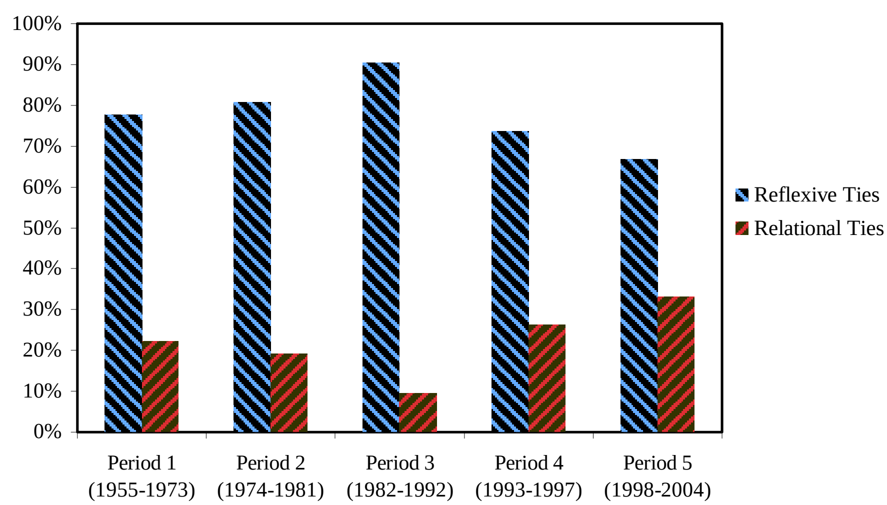

Figure 56. Reflexive and relational affiliation-type ties among authors of STE-relevant papers in the ASES conference dataset, 1955–2004, according to period

Figure 57 illustrates the shifting prominence of particular affiliation types in coauthoring STE-relevant papers at the ASES conference, according to each type's share of strong and regular ties (either on both sides or only one side of a tie) in different time periods. Unlike the PV case in which Period 1 was almost entirely dominated by university researchers, in the STE case, university researchers have the lowest share of ties in any period in Period 1 (25%). Just as in PV, however, universities have been the largest influence on coauthorship ties in the STE-relevant ASES conference papers. In Period 2, university researchers became the most prominent affiliation type, a situation that continued throughout the other periods. The largest proportion of ties accounted for by university researchers occurred in Period 4 (60%). Government and non-utility firms also account for a large number of ties in the STE-relevant ASES conference papers. Their largest share of ties occurred in Period 1 (again, in opposition to the PV case), with government accounting for 33% of ties and non-utility firms for 42% of ties. After dropping in Period 2 (24%), government ties remain fairly constant for the other periods, at 19% in Period 3, 22% in Period 4, and 17% in Period 5. Non-utility firms exhibit a similar decline in Period 2 (28%), but the decline continues in Period 3 (21%) and Period 4 (17%), only beginning to rebound in Period 5 (29%). The low proportion of non-utility firm ties in Period 3 is a further indication that the work being done in the SEGS plants might not have been fully presented in the ASES conference; again, further work will be necessary to address this.

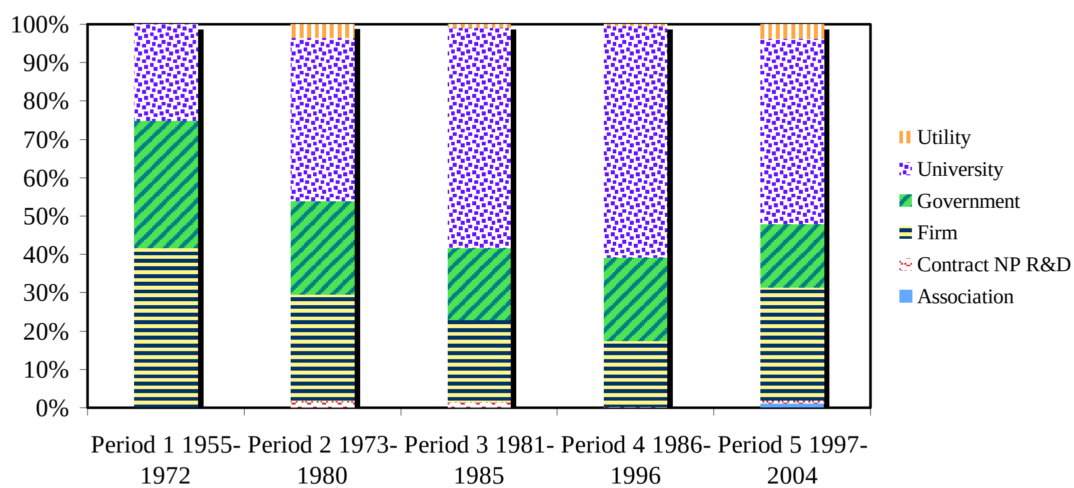

Figure 57. Strong and regular affiliation-type ties on STE-relevant papers in the ASES conference dataset, 1955–2004, according to period

3.5. Experience Curves

Quantitative modeling of "experience curves" has become an increasingly common method of representing endogenous technical change in long-term integrated assessment models used for energy and environmental policy analysis. This section focuses on quantifying the outcomes of innovation in STE technology by developing experience curves, which relate improvements in the cost or performance of a technology to the cumulative production of that technology. Experience curves are based on an organizational learning curve, the classical formula for which is given below.[85]

$$y_i = a x_i^{-b}$$

where:

y = the number of labor hours required to produce the ith unit
a = the number of labor hours required to produce the first unit
x = the cumulative number of units produced through time period i
b = the learning rate
i = a time subscript

The x-variable in this equation is a proxy for knowledge acquired through production. It is computed by summing the total units of output produced from the start of production up to, but not including, the current year (this is because of the standard assumption that experience acquired over the course of a given year will not be reflected in technical improvements in the year the experience is gained). In the STE case, the “output” considered for the x-variable is the cumulative megawatts of electrical capacity (MW) generated by STE technology. As the SEGS units in California were the only commercial systems in operation in late 2005, when this analysis was completed, they provide the data source for the x-variable in this analysis.

The y-variable in the experience curve equation is represented by four attributes in this analysis: capital costs; operating and maintenance costs; pump failures (a measure of reliability); and generating efficiency.[86] These y-variables are linked to different phases of experience with the SEGS units. Table 19 depicts the y-variables and relevant installations and operating years used for the x-variables in this section. Figure 58, Figure 59, Figure 60, and Figure 61 depict the experience curves—on a log-log scale—regarding the costs, reliability, and generating efficiency of commercial STE units as cumulative generation (lagged by one year) increases. The main sources used in constructing these figures are: Lotker (1991); Johansson, Kelly et al. (1993); Grosskreutz (1996); Cohen, Kearney et al. (1999); Enermodal (1999); Sargent & Lundy (2002); and Kearney and Price (2005).

Table 19. Experience curve data for commercial systems (SEGS units in California)

Technology Characteristics for Y-Variable	Relevant Installations	Years MW Generated for X-Variable
Capital Costs	New	1985–1991
Operating & Maintenance Costs	Existing	1992–1998
Pump Failures (Reliability Metric)	Existing	1990–1998

[85] For a comprehensive review of organizational learning curves, see Argote (1999).

[86] All costs are in constant 2004 dollars.

Generating Efficiency	New	1985–1991

Figure 58 is an experience curve of the capital cost of newly installed SEGS units in \$/Watt. The line shown is the best-fit of a power function relating the x- and y-variables; at 0.12, the goodness-of-fit is very weak. The parameter b (-0.05) in the equation—the learning rate—translates into a progress ratio of $2^{-0.05}$, or 0.97.[87] This means that as cumulative output doubles, the capital cost of new STE installations declined only to 97% of original levels, which is quite flat. However, the data in Figure 58 is the *actual* capital cost of SEGS systems; as in most power plants, these costs can entail a great number of site-specific design factors, particularly if the unit size varies as in the case of the SEGS systems over time. In previous work on other technologies, for example (Taylor, Rubin et al. 2003), in place of actual capital cost data, the author relied on a series of capital cost studies and converted some of the assumptions in those studies to a benchmark power plant (with a benchmark fuel source) using a computer model of coal-fired power plants. In the STE case, a similar model was not available. Figure 58, since it does not account for system size, should be considered somewhat uncertain. There is reason to believe that the uncertainties in Figure 58 are offsetting, however, at least in terms of direction, if not magnitude. For example, the SEGS units increased in size over time, which created economies of scale. This would indicate that the slope of the line in Figure 58 overestimates learning-by-doing. On the other hand, performance improvements also occurred in the SEGS units, some of which enabled higher capacity factors. These improvements suggest that Figure 58 underestimates learning-by-doing.

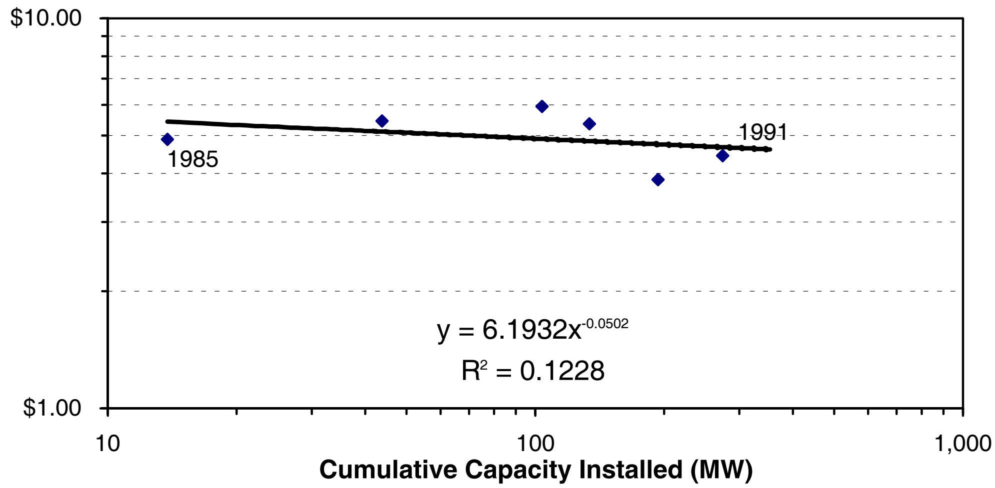

Figure 58. Experience curve for the capital cost of STE plants

Figure 59 is an experience curve of the operating and maintenance costs involved in running the SEGS units. The best-fit line shown, a power function relating the x- and y-variables, has a relatively strong goodness-of-fit at 0.93 (the strongest in the STE case). The parameter b (-0.63) in the equation—the learning rate—translates into a progress

[87] All numbers derived from equations in Figure 58, Figure 59, Figure 60, and Figure 61 are presented in the text of this section to the second decimal point.

ratio of 0.65. This means that as cumulative output doubles, STE operating and maintenance costs decline to 65% of their original levels, which is considerably better than the most frequently observed progress ratio in such industries as electronics, machine tools, papermaking, aircraft, steel, and automobiles, which is 80% (Dutton and Thomas 1984). The strong improvement in operating and maintenance costs shown here may have been enhanced by a Luz-Sandia partnership which identified opportunities for improving the operating performance and costs of the SEGS units.

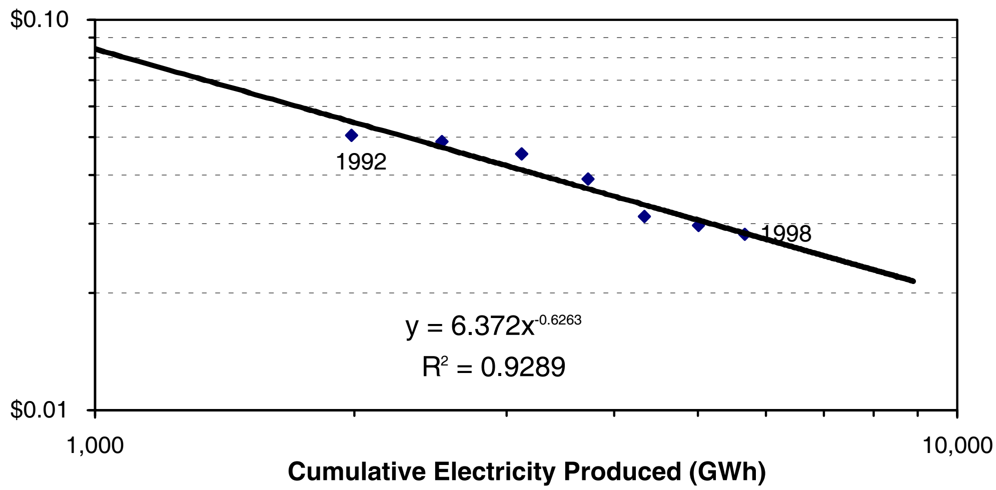

Figure 59. Experience curve for the operating and maintenance costs of STE Plants

Figure 60 is an experience curve of the reduction in pump failures in the SEGS plants, a metric of reliability (and opportunity for improvement found in the aforementioned Luz-Sandia partnership) that improved by two orders of magnitude over the course of the 1990s. The best-fit line shown, a power function relating the x- and y-variables, has a decent goodness-of-fit at 0.70. The parameter b (-2.17) in the equation—the learning rate—translates into a progress ratio of 0.22. This means that as cumulative output doubles, pump failures decline to 22% of their original levels.

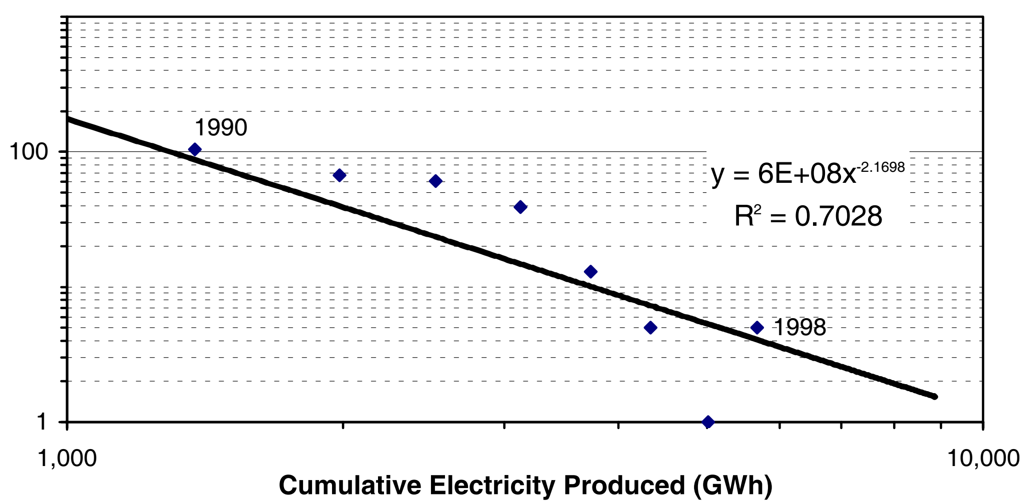

Figure 60. Experience curve for pump failures in STE plants

Figure 61 is an experience curve of the generating efficiency (electrical conversion efficiency) of STE plants. The best-fit line shown, a power function relating the x- and y-variables, has a decent goodness-of-fit at 0.71. The line is positive, reflecting efficiency improvements that have accrued with experience, and relatively flat. The parameter b (0.09) in the equation—the learning rate—translates into a progress ratio of 1.07, just as in the case of PV modules (see Figure 37). This means that as cumulative output doubles, STE plant efficiencies reach 107% of their original levels.

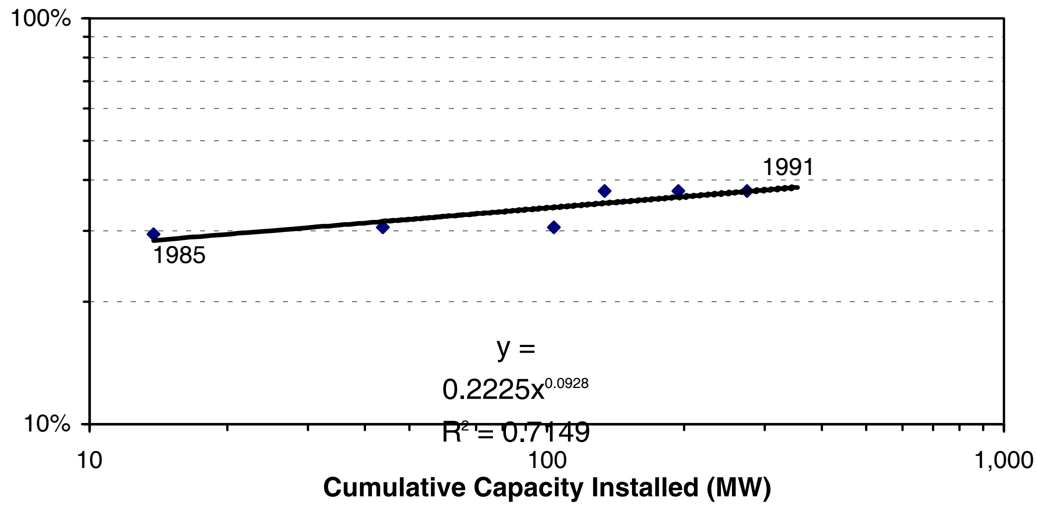

Figure 61. Experience curve for the efficiency of STE plants at time of construction

4.0 Solar Water Heating

This chapter examines the effect of government actions on innovation in domestic solar water heating (SWH) technology. The chapter includes: (1) an overview of the technology, including major developments; (2) an assessment of inventive activity and its relationship to government actions, as addressed through analysis of patenting activity; and (3) a consideration of the importance and dynamics of knowledge transfer in the development of SWH, as addressed by expert interviews and a graphical and network analysis of conferences pertinent to the technology. Following this treatment of the innovation process and its relationship to government actions, the chapter concludes with a treatment of the outcomes of innovation, as measured through experience curves relating technological diffusion to performance and cost improvements.

4.1. Technology Overview

All technologies that convert incoming solar radiation into thermal energy, either for use directly as heat, in the case of SWH, or for conversion into electricity, as in the case of STE, are considered "solar thermal" technologies (Larson and West 1996). Since the 1970s, the federal government has applied four categories to solar thermal technologies: "(1) active solar heating and cooling; (2) passive solar heating and cooling; (3) industrial process heat; and (4) solar thermal electricity" (ibid., p. 4).[88] This chapter focuses on SWH technologies, which it defines as solar thermal hot water systems that provide domestic water heating, which is a significant component of residential energy use.[89] Today's SWH units, when properly installed, will typically reduce the need for conventional water heating by about two-thirds (EERE 2006b).

Solar water heating systems raise the temperature of a circulating working fluid by exposing the fluid to solar radiation via a collector. In some systems, the "working fluid" heated by the collector is potable water to be used in residential applications; in others, the fluid (which might be air) circulates and transfers heat to potable water through indirect contact via tubing (EERE 2006b). Heated potable water is typically stored in a well-insulated tank. In most cases, SWH systems work as hybrid systems in conjunction with a supplemental natural gas-powered or electric heater. The configuration of the SWH and the conventional heater is one of several design elements that distinguish SWH systems. If the two heaters—solar and conventional—use a single water tank, "the back-up heater is combined with the solar storage in one tank"; if the two heaters have separate tanks, the SWH unit "preheats water before it enters the conventional water heater" (EERE 2006b).

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[88] Most federal solar commercialization efforts "through the early 1980s were directed at the four solar thermal areas because they were perceived to be nearest to commercial viability" (Larson and West 1996, p. 4).

[89] In the United States, water heaters account for 13% of residential energy use, consuming 100 billion kWh of electricity, 1 trillion cubic feet of natural gas, 900 million gallons of fuel oil, and over 500 million gallons of liquefied petroleum gas (LPG).

A second distinguishing characteristic amongst SWH systems is whether the system is "active" or "passive." The term "active" refers to a SWH system with a pump and controls that assist in fluid circulation (Larson and West 1996). The term "passive" indicates that the SWH system employs little to no "mechanical or electrical energy to move fluids" (ibid.). Passive SWH systems are typically less expensive and less efficient than active systems, and may be more reliable and long-lasting (EERE 2006b).

There are two types of active SWH systems: (1) direct circulation and (2) indirect circulation (EERE 2006b).

(1) *Direct circulation systems*: In these systems, potable water circulates, with the assistance of a pump, "from the water storage tank [located inside the house] through one or more collectors and back into the tank" (Block and Harrison 1997). The solar collector is usually a glazed flat-plate collector, which is basically a "metal box with insulation and a black absorber plate that collects solar radiation and heats the water" (ibid.); the collector area is typically 25–80 square feet and the storage tank about 300 liters (Brechlin, Pilgaard et al. 2003). The circulating pump is regulated by "an electronic controller, a common appliance timer, or a photovoltaic panel" (ibid.). The speed of the pump is adjusted based on the intensity of the sunlight. Water is recirculated through the system until temperatures are hot enough for domestic use. Temperature sensors are located at the outlet of the collector as well as at the bottom of the storage tank. When the sensor in the collector registers a temperature that is 15 to 20 degrees warmer than the storage tank, the pump circulates water from the collector to the tank. If the temperature difference drops below that level, as the sun drops late in the day, the pump shuts off. A typical direct circulation SWH system is illustrated in Figure 62.

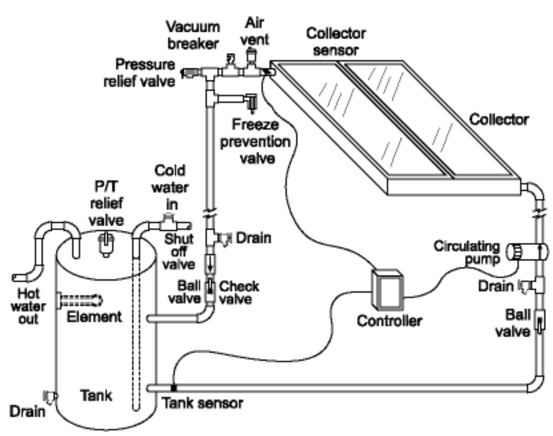

Figure 62. Schematic of a direct circulation (active) SWH unit

Source: (Block and Harrison 1997)

(2) *Indirect circulation systems*: In these systems, "pumps circulate a non-freezing, heat-transfer fluid through the collectors and a heat exchanger" (EERE 2006b). The heated fluid "circulates in tubes through the water storage tank, transferring the heat from the fluid to the potable water" (EERE 2006b). Indirect circulation systems "are popular in climates prone to freezing temperatures" (EERE 2006b).

There are also two main types of passive SWH systems: (1) integral collector-storage and (2) thermosiphon (EERE 2006b).

(1) *Integral collector-storage*: These systems (ICS, also known as "batch" systems), are named for their distinctive solar collectors which "feature one or more black tanks or tubes in an insulated, glazed box" (EERE 2006b). The collector preheats potable water, which then "continues on to the conventional backup water heater" (ibid.). Figure 63 illustrates an ICS SWH unit. Note that because the water-bearing pipes in the collector are essentially outdoors, these systems are particularly subject to problems with freezing. The popular "Climax" and its successor SWH systems in the early decades of the twentieth century were ICS systems.

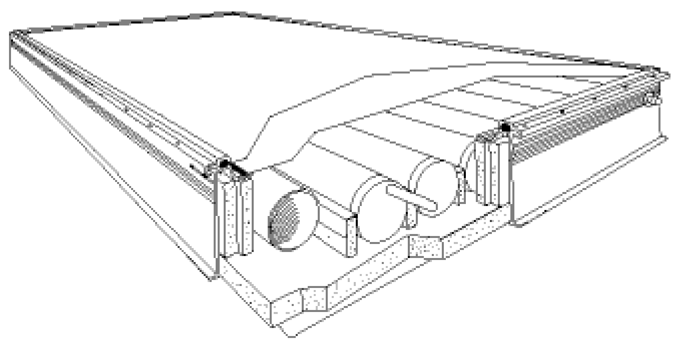

Figure 63. Schematic of an integral collector-storage (passive) SWH unit

Source: (Block and Harrison 1997)

(2) *Thermosiphon*: These systems use the "thermosiphon" principle in which warm water—heated in the collector—rises into a storage tank installed above the collector. The storage tank is heavy, which can cause installation problems, but the systems are generally quite reliable. Thermosiphon systems are usually more expensive than ICS systems.

The U.S. government has been tracking data on solar collector manufacturing in "shipments" data going back to 1984. The three tables that follow compile much of the data regarding SWH shipments and companies over time. Shipments of SWH are contained in the terms "low-temperature solar collectors" and "medium-temperature" solar collectors.

Low-temperature collectors generally operate below 110 degrees Fahrenheit. These collectors dominate shipments of solar collectors, as illustrated in Table 20 and Table 22 (this also holds true if one considers high-temperature collectors—the category that includes STE architectures—as in Table 13 in the STE chapter). The main end-use of low-temperature collectors, as illustrated in Table 21, is to heat swimming pools, rather than provide a source for domestic hot water, which is the focus of this chapter. Note that low-temperature collectors are typically plastic and much less expensive than other collectors (see Table 20 and Table 22).

Medium-temperature collectors generally operate between 140 degrees Fahrenheit and 180 degrees Fahrenheit, but can also operate at temperatures as low as 110 degrees Fahrenheit. "Special collectors," such as "evacuated tube collectors or concentrating (focusing) collectors," fit in this category, as "they operate in the temperature range from just above ambient temperature (low concentration for pool heating) to several hundred degrees Fahrenheit (high concentration for air conditioning and specialized industrial processes)" (EIA 2006b). Although a small portion of overall solar collector shipments, as illustrated in Table 20, the main end-use of medium-temperature collectors is domestic water heating, as illustrated in Table 21. As such, these collectors are the ones that have been the focus of a considerable amount of policy effort through the 1970s and 1980s, as discussed in the introduction chapter to this report. Table 22 shows how the relative fortunes of medium-temperature solar collectors have changed over time; these changes map the changes in SWH incentives.

Table 20. Solar thermal collector shipments by type, quantity, value, and average price, 2004

Type of Collector	Quantity (1,000 ft^2)	Value ($1,000)	Average Price ($/ft^2)
Low-temperature (Liquid + Air)	13,608	24,545	1.80
Medium-temperature	506	9,769	19.30
Air	4	W	W
Liquid			
ICS/Thermosiphon	118	2,772	23.57
Flat Plate	383	6,802	17.75
Evacuated Tube	2	W	W
Concentrator			

Source: (EIA 2006b, Table 37). W indicates that data were withheld to avoid disclosure of proprietary company information.

Table 21. Solar thermal collector shipments by end use, market sector, and type, 2004

	Low-temperature Collectors (1,000 ft^2)	Medium-temperature Collectors (1,000 ft^2)	Total (Low + Medium, 1,000 ft^2)
End-Use Total	**13,608**	**506**	**14,114**
Pool Heating	13,600	33	13,634
Water Heating	0	452	452
Space Heating	8	5	13
Space Cooling	0	0	0
Combined Space and Water Heating	0	16	16
Process Heating	0	0	0
Electricity Generation	0	0	0
Other	0	0	0
Market Sector Total	**13,608**	**506**	**14,114**
Residential	12,386	478	12,864
Commercial	1,178	0	1,178
Industrial	44	26	70
Electric Utility	0	0	0
Other	0	3	3

Source: (EIA 2006b, Table 10.4)

Table 22. Low-temperature and medium-temperature solar thermal collector shipments by type and price

	Low Temperature Collectors				Medium Temperature Collectors				
Year	# of U.S. Mfrs.	Quantity Shipped	Shipments per Mfr.	Price ($/ft^2)	# of U.S. Mfrs.	Quantity Shipped	Shipments per Mfr.	Price ($/ft^2)	Total Shipments
1974	6	1,137	190	NA	39	137	4	NA	1,274
1975	13	3,026	233	NA	118	717	6	NA	3,743
1976	19	3,876	204	NA	203	1,925	10	NA	5,801
1977	52	4,743	91	NA	297	5,569	19	NA	10,312
1978	69	5,872	85	NA	204	4,988	25	NA	10,860
1979	84	8,394	100	NA	257	5,856	23	NA	14,251
1980	79	12,233	155	NA	250	7,165	29	NA	19,398
1981	75	8,677	116	NA	263	11,456	44	NA	21,133
1982	61	7,476	123	NA	248	11,145	45	NA	18,621
1983	55	4,853	88	NA	179	11,975	67	NA	16,828
1984	48	4,479	93	NA	206	11,939	58	NA	16,418
1985	NA	NA	NA	NA	NA	NA	NA	NA	NA
1986	22	3,751	171	2.3	87	1,111	13	18.3	4,862
1987	12	3,157	263	2.18	50	957	19	13.5	4,114
1988	8	3,326	416	2.24	45	732	16	14.88	4,058
1989	10	4,283	428	2.6	36	1,989	55	11.74	6,273
1990	12	3,645	304	2.9	41	2,527	62	7.68	6,172
1991	16	5,585	349	2.9	41	989	24	11.94	6,573
1992	16	6,187	387	2.5	34	897	26	10.96	7,084
1993	13	6,025	464	2.8	33	931	28	11.74	6,956
1994	16	6,823	426	2.54	31	803	26	13.54	7,625
1995	14	6,813	487	2.32	26	840	32	10.48	7,653
1996	14	6,821	487	2.67	19	785	41	14.48	7,606
1997	13	7,524	579	2.6	21	606	29	15.17	8,131
1998	12	7,292	607	2.83	19	443	23	15.17	7,735
1999	13	8,152	627	2.08	20	427	21	19.12	8,579
2000	11	7,948	723	2.09	16	400	25	W	8,349
2001	10	10,919	1,092	2.15	17	268	16	W	11,187
2002	13	11,126	856	1.97	17	535	31	W	11,661
2003	12	10,877	906	2.08	17	560	33	W	11,437
2004[P]	9	13,608	1,512	1.8	17	506	30	19.3	14,114

Source: (EIA 2006b, Table 10.3)
NA indicates that there is no applicable data. P indicates that the data is preliminary.

Solar collector manufacturing is dominated by a small number of companies. Data from 1996–2001 show that collector manufacturing is highly concentrated, with the top five companies representing a high of 96% of total shipments in 2001 and a low of 85% in 1996 (EIA 2006). The solar thermal industry is not completely dedicated to collector manufacturing, however. Table 23 characterizes the U.S. solar water heating industry by the total number of companies engaged in specific solar thermal-related activities.

Table 23. Companies Involved in Solar Thermal Collector Activities by Type, in 2004 and 2005

Type of Activity	2004	2005[P]
Collector or System Design	19	22
Prototype Collector Development	10	11
Prototype System Development	8	11
Wholesale Distribution	22	23
Retail Distribution	11	11
Installation	8	9
Noncollector System Component Manufacture	11	10

Source: (EIA 2006b, Table 43)

P indicates that the data is preliminary.

Major innovations in SWH systems have occurred in four technical areas: (1) selective coatings, (2) polymer-based systems, (3) external heat exchangers, and (4) absorber plates.

1. *Selective Coatings*: According to experts interviewed for this report, "the most significant advance in solar water heaters by far was the development of selective coatings on the absorbers." Early systems were coated by a plain black paint that absorbed nearly all of the incoming solar radiation. As the light was connected to heat inside the coated material, infrared (IR) radiation was able to leak out. Selective coatings stopped the leakage and returned the IR radiation to the working fluid, raising the amount of heat absorbed by approximately 20%. This technology emerged originally out of Israel in the late 1960s and was developed by United States federal laboratories in the early 1970s.

2. *Polymer-based systems:* Experts believe that the biggest breakthrough in SWH since selective coatings emerged in the 1970s is the advent of polymer-based, rather than steel and glass-based, collector systems. Polymer-based systems can reduce the installed cost of SWH by a factor of three; the first polymer-based system, which will cost just over $1000 per installed system, was scheduled to be installed in 2006.

   A critical issue with polymer-based systems is whether years of exposure to ultra-violet (UV) radiation will cause the plastic to degrade and possibly lead to leakage. UV-reflective coatings, developed to prevent material degradation for swimming pool heating is proving to be useful in addressing this challenge. Although the private sector has contributed to the development of polymer-based systems through the original experimentation at DuPont and recent cost-sharing with the public sector, experts credit federal laboratories with the crucial role in developing this technology.

3. *External heat exchangers:* Another cost-saving improvement in SWH has been the relocation of the heat exchanger to outside the water tank. This change has allowed the integration of mass-produced—rather than designated—hot water tanks into SWH system design. This has reduced the cost of storage in the systems by 50%.

4. *Absorber plates*: Cost reductions in absorber plates have come about because of the use of a heat-absorbing and heat-transferring component inside the thermal collector, as well as the switch to thinner absorber plate materials.

4.2. Government Actions

The complexity of the solar policy history presented in the introduction to this report, which is in part due to the fact that many of the policy instruments designed to promote solar over the years applied to more than one solar technology, prompted an appeal to experts to sort through the relative importance of various government actions on technological innovation in SWH.[90] Table 24 and Figure 64 compile the responses of the experts interviewed for this report on this issue. Experts ranked government actions on a scale of 1–5, with 5 having the most important effect (negative or positive) on the industry and the development of the technology.

[90] Appendix B details the procedure with which we selected experts, as well as our interview methodology and protocol.

Table 24. Expert opinion of importance of government actions to innovation in SWH

Government Action	Expert A	Expert B	Expert C	Expert D	Expert E	Expert F	Expert G	Average Score (Scale 1–5, with 5 most important)
1978–85 Federal tax credits (25% increasing to 40%)	4	5	5	5	5	5	5	4.9
1996 Hawaii Elec. Co. program ($750–$1000/system)	5	5	5		5	5	4	4.8
1977–83 CPUC solar hot water tax credits (55%)		5	5		5	5	4	4.8
1974–83; 1991–present resid. renewable energy tax credits	4	5	5			4		4.5
1995 Germany "Market Stimulation Program" (~$10/sf)							4.5	4.5
1981–86 Energy conservation tax credit (40%)	3					5		4.0
Late 1970s Licensing required for installers	5	2	4		5	5	3	4.0
1974–05 United States Federal Solar Hot Water R&D Program	4	1	4	5	3	3	4	3.4
1978 Solar Rights Act (bars zoning restrictions on SHW)	1	2	2		5	5	2	2.8
2002 DoE Zero-Energy Buildings Initiative	1	2	4	2	4	2	4	2.7
1992 SMUD Solar Dom. Hot Water Program ($400/system)	4		4		1	1	3	2.6
1978–present Business Energy Tax Credit (10%)	1	1	3	3	3	5	1	2.4
1978 Japan "Moonlight Project" (energy efficiency R&D)								-
1990s China technology and quality standards								-

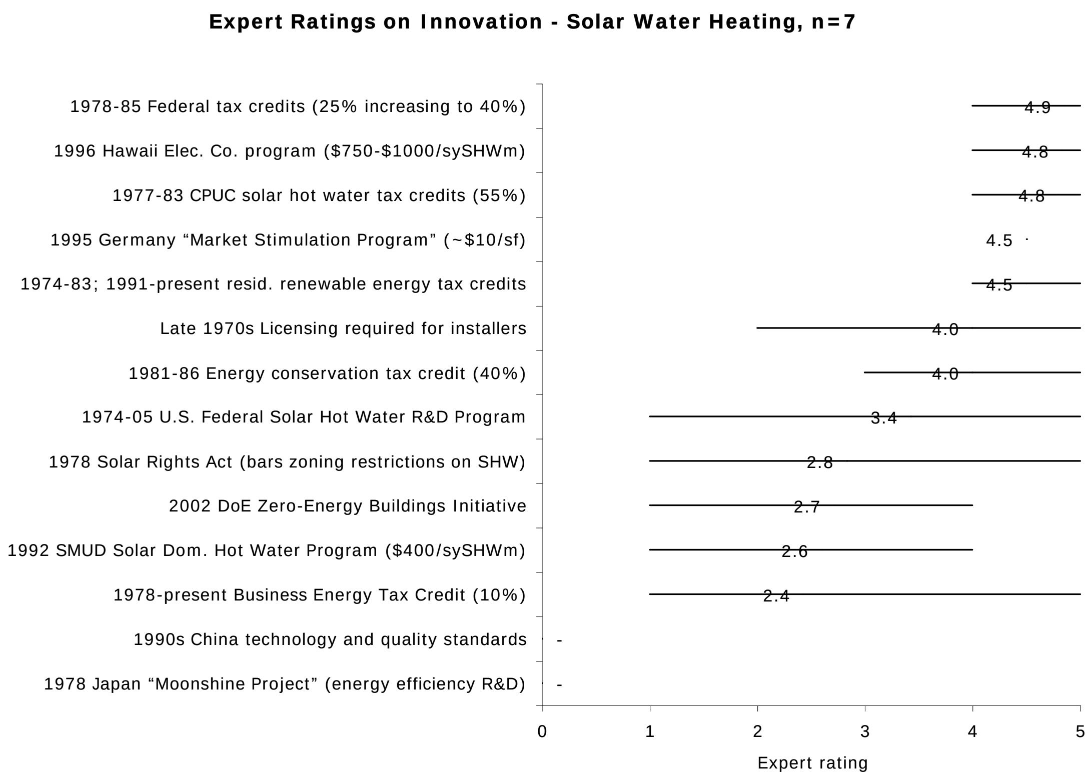

Figure 64. Expert ratings of policies relevant to SWH

4.3. Inventive Activity

Two metrics are often used in the economics of innovation literature to give insight into inventive activity: R&D funding is used as an input metric, while patents are used as an output metric. This section will only treat the analysis of patenting activity in STE, as the introduction chapter to this report discusses various solar energy R&D programs in the United States, California, Germany, and Japan. Figure 1, Figure 3, Figure 4, Figure 6, and Figure 7 all contain national solar energy R&D data.[91]

As outlined in the introduction to this report, two patent datasets—a “class-based” dataset and an “abstract-based” dataset—were created for this analysis using two different approaches to manipulating patent data. Details on the construction of these datasets can be found in Appendix A and in Section 1.3.1 of this report.

Inventors have different reasons for filing (or not filing) patents, depending on their perception of the economic value of patents in their industry. In any technology-based industry targeted for patent analysis, it is important to try to understand this perception in order to place the results of analysis in context. In the SWH industry, the experts interviewed for this analysis had divergent opinions about whether patents covered the major innovations, with three saying they covered some of the major innovations, two

[91] Preliminary work shows that California’s solar energy R&D is not insignificant, although it has proven to be too difficult to compile into a comprehensive time-series in time for the publication of this report.

saying they were unsure, and two saying that patents did not cover the major innovations. One response was that the "technology is not that sophisticated, so there is not much to patent" and another that there was lots of patenting in the 1970s because "in the '70s, the weirder it looked, the better it sold." One who answered that patents did cover the major innovations qualified it by saying "yes, but there was almost no innovation."

4.3.1. Datasets

The class-based dataset of SWH patents netted 2,073 patents granted between 1858 and 2002. Figure 65 portrays this dataset according to the patent application date, which is the earliest date that can be consistently tied to the inventions that are granted patents. As there is generally a two-year lag between the patent application date and the date the patent is granted, the dataset in Figure 65 ends in 2002 (as do most of the patent figures in this report). Note that this dataset is not "clean," as patents in this figure were not coded for relevance to SWH.

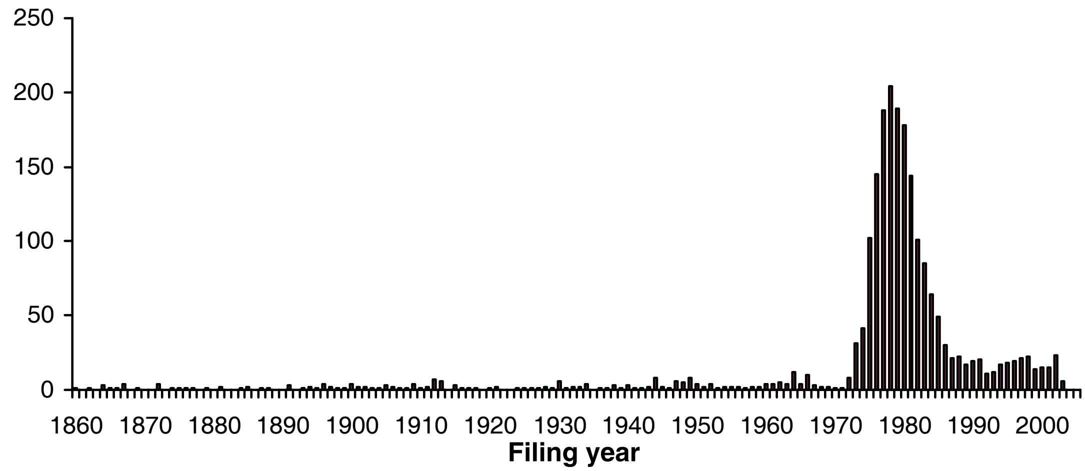

Figure 65. Class-Based Dataset of SWH Patents, by Application Date, 1858-2002

Although the class-based dataset is consistent for over 100 years, and thus, can be used to relate patenting trends to the timing of long-past government actions related to the technology, the tradeoff for the length of this dataset is that it is less certain with respect to under-counting and over-counting than are other approaches to patent analysis. As in the other technology cases in this report, an "abstract-based" was created to complement the class-based dataset and in part.

The abstract-based approach to creating a patent dataset for SWH netted 1,291 patents granted between 1975 and 2002. Figure 66 shows the abstract-based patent dataset for SWH, according to the patent application date. Note that this dataset is "clean," as patents in this figure were coded for relevance to SWH. The coding of the abstract-based dataset, and initial samples of the class-based dataset, indicate that the coded abstract-based dataset is a more reliable patent dataset to understand SWH technology. For this reason, analyses in this SWH chapter—unlike the PV chapter—are based on the abstract-based dataset.

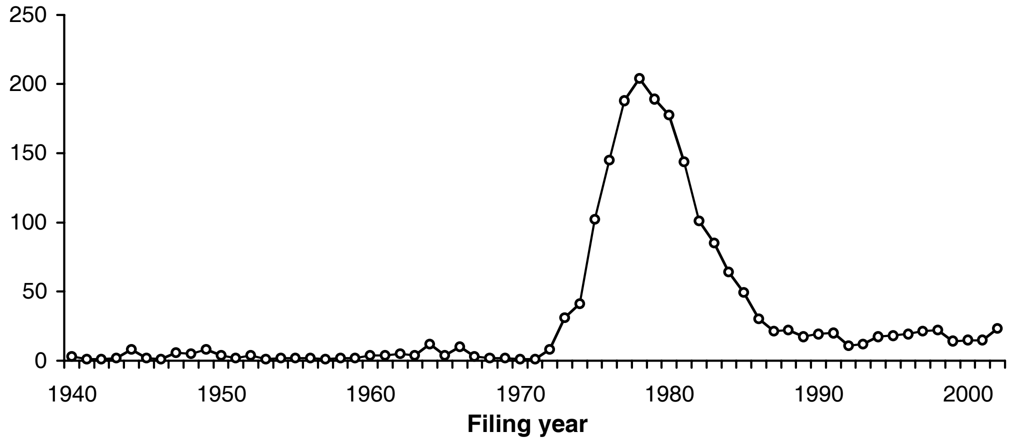

Figure 66. "Clean" abstract-based dataset of SWH patents, by application date, 1940–2002

Like the class-based dataset, the "clean" abstract-based patent dataset shows that overall SWH patenting activity peaked in the late-1970s.

4.3.2. Descriptive Statistics

Table 25 shows the top ten patent holders in the "clean" SWH abstract-based patent dataset. Note that, like the STE case and unlike the PV case, the most significant patent holder in SWH is the U.S. government. Unlike the STE case, two other public sector organizations are in the top-ten patent holder list: the United States Secretary of the Navy and the Commissariat a l'Energie Atomique (the French Atomic Energy Commission). The variation between the three cases is interesting, as all three solar energy technologies received significant public R&D subsidies. In addition, it is interesting to note that there is some overlap between the top patent holders in the three solar technologies: Owens-Illinois Inc. is a top-ten patent holder in both STE and SWH, while Sharp Kabushiki Kaisha is a top-ten patent holder in both PV and SWH.

Table 25. Top ten patent holders in the "clean" SWH abstract-based patent dataset

Patent Owner	Country	Number of Patents	% of Total
The United States of America	United States	10	0.9
Owens-Illinois, Inc.	United States	8	0.7
Sharp Kabushiki Kaisha	Japan	6	0.6
Corning Glass Works	United States	6	0.6
Alpha Solarco Inc.	United States	6	0.6
Grumman Aerospace Corporation	United States	5	0.5
Honeywell Inc.	United States	5	0.5
Raytheon Company	United States	4	0.4
United States Secretary of the Navy	United States	4	0.4
Commissariat a l'Energie Atomique	France	4	0.4
		Total	**5.6**

Table 25 also makes it clear that intellectual leadership in SWH technology, according to the percentage of patenting activity controlled by the top-ten patent holders (5.6%), is much less concentrated than in PV cells (56.9%) and STE technology (22.6%). This intellectual leadership is about as international as STE technology, and considerably less international than PV cells. Eight of the patent owners in Table 25 are American, one is Japanese, and one is French.

Table 26 provides a more comprehensive sense of patent ownership in the "clean" SWH abstract-based patent dataset. The percentage of patents held by the top ten patent holders identified in Table 25 (5.6%) is included in Table 26 for purposes of comparison to the percentage of patents held by individuals (54.6%) and California-based inventors (14.2%).

Table 26. Patent ownership in the "clean" SWH abstract-based dataset

Patent Ownership	Proportion in SWH Abstract-Based Dataset (%)
Top 10 Assignees	5.6
Individuals	54.6
California Inventors	14.2

Figure 67 shows all patenting activity in the "clean" abstract-based SWH patent dataset between 1974 and 2002, according to the inventor nation-of-origin. Patenting activity in the United States increased dramatically in the mid-1970s, peaking in 1977 and then dropping off dramatically, stabilizing at minimal levels in the mid-1980s. Other countries do not seem to patent significantly in this technology in the U.S. system, although the Japanese patent at higher levels in the 1970s than American entities patent at today. The patent trends in this figure reflect the decline in public policy support for SWH systems and the subsequent loss of intellectual leadership to the other industries, including the dominant low-temperature swimming pool market, as discussed in expert interviews for this report.

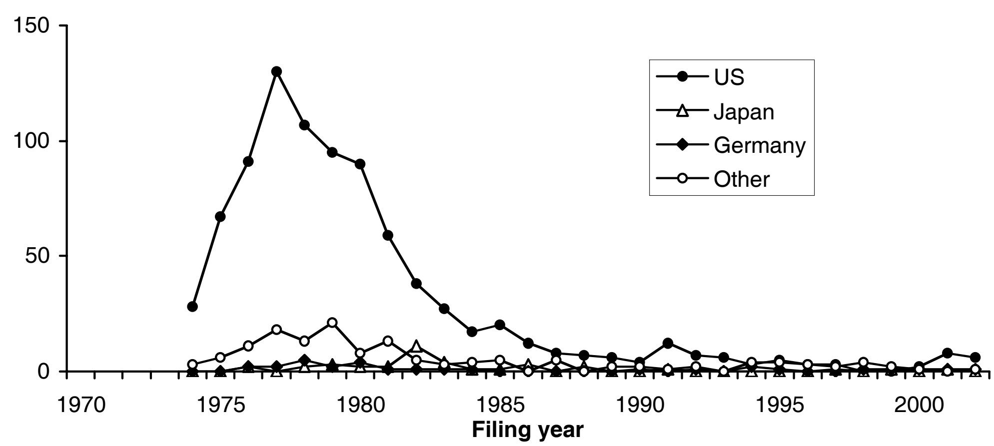

Figure 67. Patents in the "clean" abstract-based SWH patent dataset according to nation of origin and application date, 1974–2002

Figure 68 graphs federal solar water heating R&D funding and patenting activity by U.S. entities (according to inventor nation-of-origin in the "clean" abstract-based patent dataset) over time. Note that although the shapes of the curves are similar, the peak in patenting activity *precedes* the peak in public R&D funding by two years. This counter-intuitive finding should be investigated in later work.

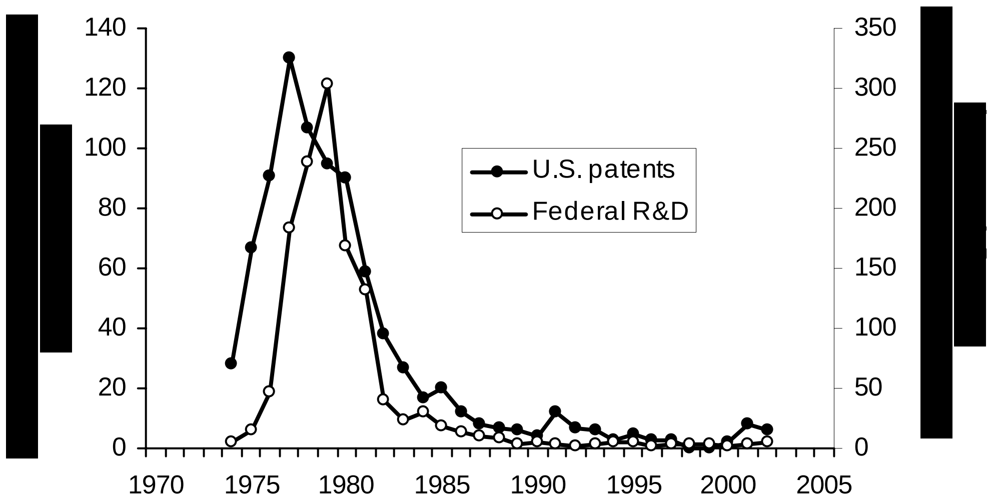

Figure 68. Federal R&D funding for solar heating & cooling and SWH patenting activity by U.S. entities, 1974–2002

Finally, Figure 69 shows the number of citations each patent in the "clean" abstract-based SWH dataset received by other patents. This is an indicator of the importance of a patent to the overall knowledge stock in a technology (the size of the circle in Figure 69 indicates the number of patents at that citation level). Figures like this are expected to exhibit a general decline in citations over time, since later patents have less time to be cited by other patents than earlier patents (it typically takes about ten years for a patent to receive most of its citations). Patents that can be considered "highly cited" in Figure 69 are those that rise highest above the average citations.

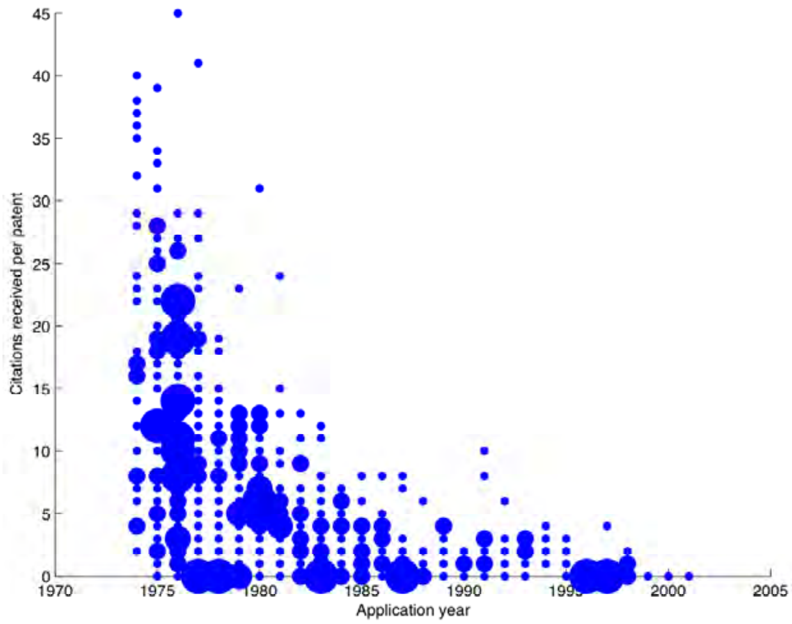

Figure 69. Patents in the "clean" SWH abstract-based patent dataset, by citations received

4.4. Knowledge Transfer Activity

This section focuses on the importance and dynamics of knowledge transfer in SWH, as addressed by a graphical and network analysis of STE-relevant technical conferences.

4.4.1. Data

The conference analyzed for this report is the set of (roughly) annual ASES conferences. These conferences provided technical papers (in addition to other material) on all three technologies—PV, STE, and SWH—for a long period of time. The first conference included in this dataset was held in 1955 by the pre-cursor to the ASES, the Association for Applied Solar Energy (AFASE); the last was held in 2004.[92] The conference occurred sporadically between 1955 and 1976, when it became an annual event.[93]

Because the papers in the ASES conference address a wide range of "solar" technologies, including the three in this report as well as others, papers in the conference dataset had to be coded for their relevance to SWH technology. Of the 4,243 papers presented between 1955 and 2004, 25% (1,096) were coded as SWH-relevant papers. Figure 70 displays the number of papers deemed relevant to SWH in each year of the ASES conference dataset. Appendix C includes details about the ASES conference dataset and how it was constructed and coded. Dataset details include the locations, dates, and sponsorship of each conference, as well as information on session topics.

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[92] AFASE formed in 1954 in Phoenix, Arizona. It was renamed the SES in 1963 and the ISES in 1976.

[93] The conference was then known as the conference of the American Section of the ISES. In 1982, it became known as the conference for the ASES.

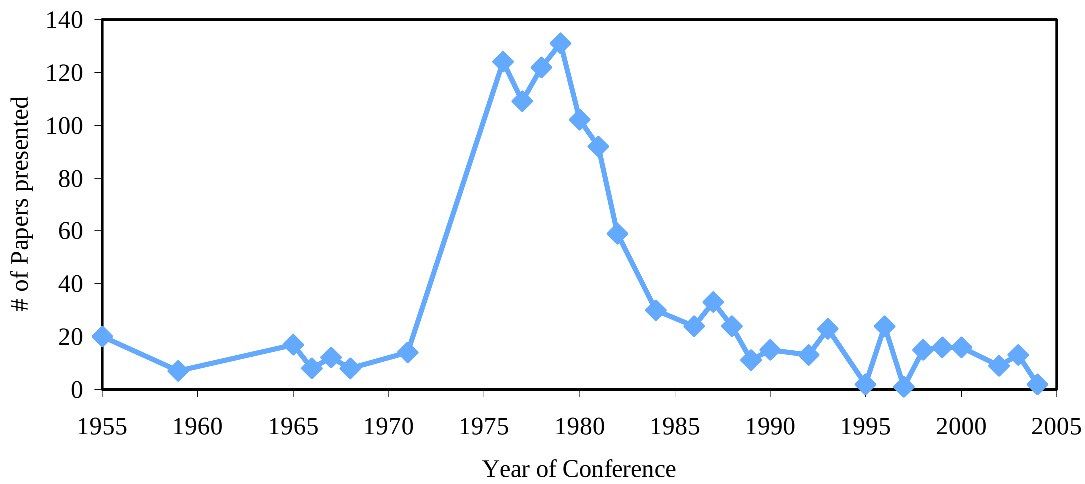

Figure 70. SWH-relevant papers in the ASES conference dataset, 1955–2004

4.4.2. Graphical Analysis

In order to appreciate the changing nature of knowledge transfer activity as government actions changed over time, this study divided the conferences in the ASES conference dataset into five periods, based on the expert interviews and the rankings of government actions given in Table 24 in the Government Actions section earlier in this chapter. Table 27 provides these periods, with notes on the context of the times, as well as the conference years included in each period.

Table 27. SWH technology periods used in knowledge transfer analysis

Period of Knowledge Transfer in SWH, with Context Notes	Conference Years in Period
1: 1955–1973 Solar losing competition w/nuclear power	1955, 1959, 1965, 1966, 1967, 1968, 1971
2: 1974–1981 Oil crises and government support for solar thermal applications like SWH	1976, 1977, 1978, 1979, 1980, 1981
3: 1982–1992 Reagan cuts, end of CPUC program, negative reaction from CA consumers	1982, 1983, 1984, 1986, 1987, 1988, 1989, 1990, 1992
4: 1993–1997 Growth in international markets	1993, 1994, 1995, 1996, 1997
5: 1998–2004 Growing state RPS movement stimulates U.S. utility interest	1998, 1999, 2000, 2001, 2002, 2003, 2004

Figure 71 shows the level of activity in the ASES conference dataset according to these periods. "Level of activity" here includes: (1) the number of SWH relevant papers (1,096); (2) the number of authors of these papers (1,440; 82% of whom write papers in only one conference); and (3) the number of organizations with which these authors were affiliated (592).

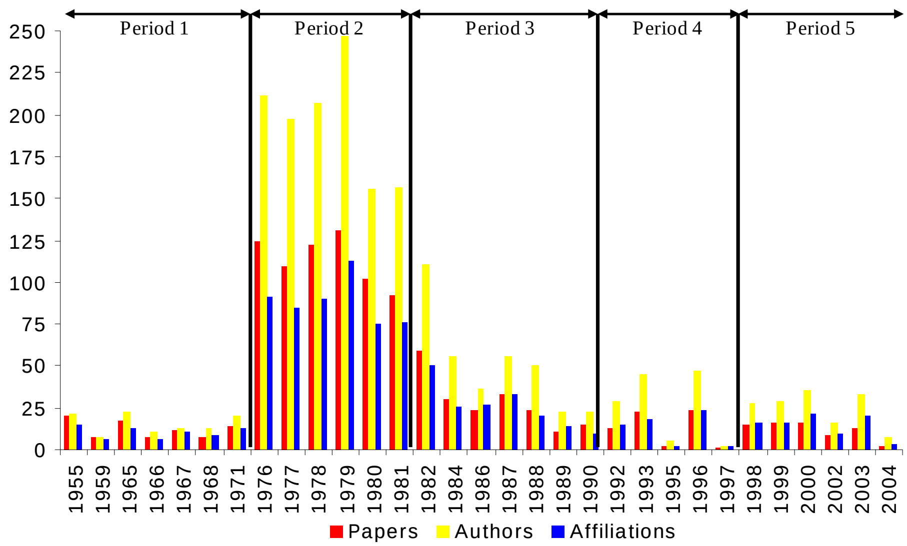

Figure 71. SWH-relevant papers, authors, and affiliations in the ASES conference dataset, 1955–2004, according to time period

The total number of authors of SWH-relevant papers in the ASES conference dataset is, in part, an artifact of the number of authors for each paper over time. Figure 72 displays the coauthorship patterns in the conference dataset for each period. For the most part, the five time periods exhibit fairly similar distributions of coauthorship, with some outliers.

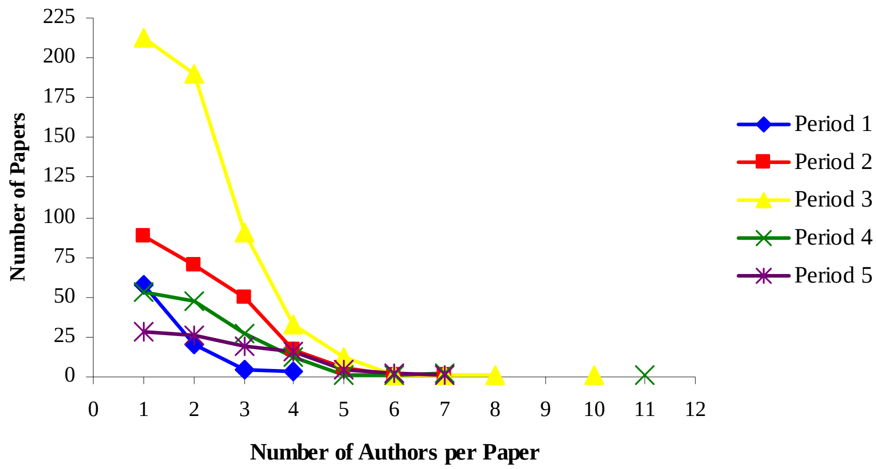

Figure 72. Coauthorship patterns in SWH-relevant papers in the ASES conference dataset, 1955–2004, according to time period

Authorship of the SWH-relevant papers in the ASES conference dataset is attributed to several types of organizations. For this reason, the SWH-relevant papers were coded for six types of organizations. "University," "utility," "firm" (not utilities), and "government" are self-explanatory organizational types. "Association" represents industry associations, such as ASES itself. "Contract NP R&D" represents contract/nonprofit R&D organizations, such as the utility industry's R&D consortium, EPRI. Figure 73 shows the results of this coding, with university, non-utility firms, and government the most prominent players in the conference, in order of decreasing importance.

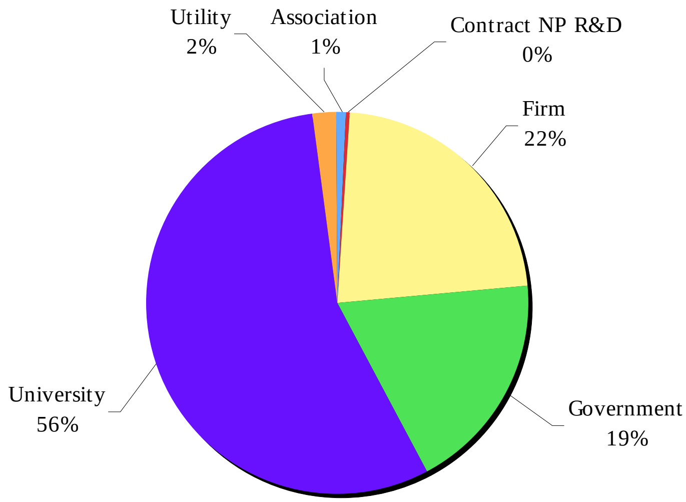

Figure 73. SWH-relevant papers in the ASES conference dataset, 1955–2004, by type of affiliate organization

Finally, Figure 74 shows how the authorship of SWH-relevant papers in the ASES conference dataset breaks down by geographic origin. The United States dominates the conference, with 85% of the total authorship, including the 7% attributed to California alone (which is smaller than might be expected given the state's prominence as an SWH market).[94]

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[94] This presumably mirrors the American sponsorship of the conference.

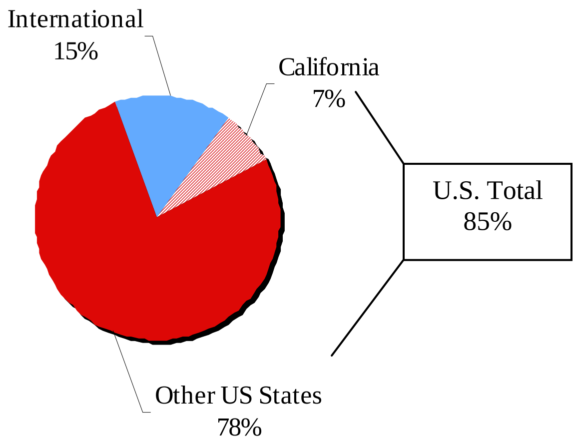

Figure 74. SWH-relevant papers in the ASES conference dataset, 1955–2004, by geographic origin

4.4.3. Network Analysis

The individuals and organizations coauthoring papers in the ASES conference form a technical communication network that can be analyzed using computational techniques developed in sociology. The basic relational data to be analyzed are the *ties* between the 1,440 authors of the SWH-relevant papers in the ASES conference dataset. In this case, a tie is a relationship between two authors. As an example, a paper with three authors—A, B, and C—has three distinct ties between them: A-to-B, B-to-C, and A-to-C. These ties can be of two types—*reflexive* and *relational*—and can vary along a few different dimensions. For example, if A and B are from the same type of organization, they are characterized as having a reflexive affiliation-type or organization-type tie. It is possible, however, that A and B are from the same type of organization but different individual organizations; in such a case, the organizational tie between them would be considered relational.

Ties can also vary based on their strength. In this analysis, a tie (or coauthor relationship) is considered *strong* if it accounts for 10% or more of the total ties in a period; a tie is considered *regular* if it accounts for between 2% and 9% of the ties in a period; and a tie is considered *weak* if it accounts for 1% or less of the total ties in a period. Table 28 presents the strong and regular ties among affiliation types, by period, according to coauthorship of PV-relevant papers in the ASES conference dataset. Although the proportion of weak ties in a given period is listed in the header row in Table 28 , weak ties are otherwise excluded from the analyses that follow. Note that the six affiliation types in the table—firms, utility, university, contract nonprofit R&D, trade association, and government—are the same as in the graphical analysis above.

Table 28. Strong and regular affiliation-type ties among authors of SWH-relevant papers in the ASES conference dataset, 1955–2004, according to period

Period 1 (1955–1973) 86 Papers 53 Ties, 0% Weak		**Period 2 (1974–1981) 680 Papers 414 Ties, 1% Weak**		**Period 3 (1982–1992) 209 Papers 892 Ties, 2% Weak**		**Period 4 (1993–1997) 50 Papers 341 Ties, 1% Weak**		**Period 5 (1998–2004) 71 Papers 277 Ties, 0% Weak**	
Univ Reflex	74%	Univ Reflex	57%	Univ Reflex	56%	Univ Reflex	64%	Univ Reflex	38%
Gov Reflex	11%	Gov Reflex	16%	Firm Reflex	15%	Gov Reflex	9%	Gov-Univ	13%
Firm Reflex	6%	Firm Reflex	12%	Gov Reflex	13%	Firm-Univ	8%	Firm Reflex	12%
Firm-Gov	6%	Firm-Univ	6%	Firm-Univ	6%	Gov-Univ	8%	Firm-Gov	10%
Firm Univ	2%	Gov-Univ	4%	Gov-Univ	4%	Firm Reflex	5%	Firm-Univ	9%
Gov-Univ	2%	Util Reflex	1%	Firm-Gov	1%	Firm-Gov	3%	Gov Reflex	7%
		Firm-Gov	1%	Firm-Util	1%	Cntrct-Firm	1%	Util Reflex	5%
		Firm-Util	1%			Assoc Reflex	1%	Assoc-Firm	3%
						Assoc-Gov	1%	Assoc Reflex	1%
						Assoc-Univ	1%	Univ-Util	1%
								Firm-Util	1%

It is clear from Table 28 that the earliest conferences in the ASES dataset did not exhibit significant coauthorship. Of the eighty-six papers presented in Period 1 of the conference, only fifty-three ties occurred. All but five were reflexive—that is, university authors coauthoring with other authors from universities and government authors coauthoring with other authors from government. But coauthorship grew, and no other period exhibits a greater number of papers than ties. Table 28 points out that total ties were at their highest in Period 3 (892 ties for 209 papers), the period in which California policy supported tremendous growth in SWH installations. The second highest ties (and the highest number of papers) occurred in Period 2, the hopeful solar era when public R&D levels for solar energy technologies—including solar thermal—were quite high. Period 5 displays the most diverse cross-affiliation type ties of the five periods (in terms of the number of affiliation-type ties exhibited in Table 28), with Period 4 the next most diverse.

As illustrated in Figure 75, most of the ties in Period 1 were reflexive; this indicates that the papers presented to the ASES conference in that period exhibited little direct research contribution from the diverse approaches and perspectives represented by cross-affiliation type relational ties. The proportion of relational ties increased across the five time periods, however, so that by Period 5, they accounted for 38% of all ties in SWH-relevant papers.

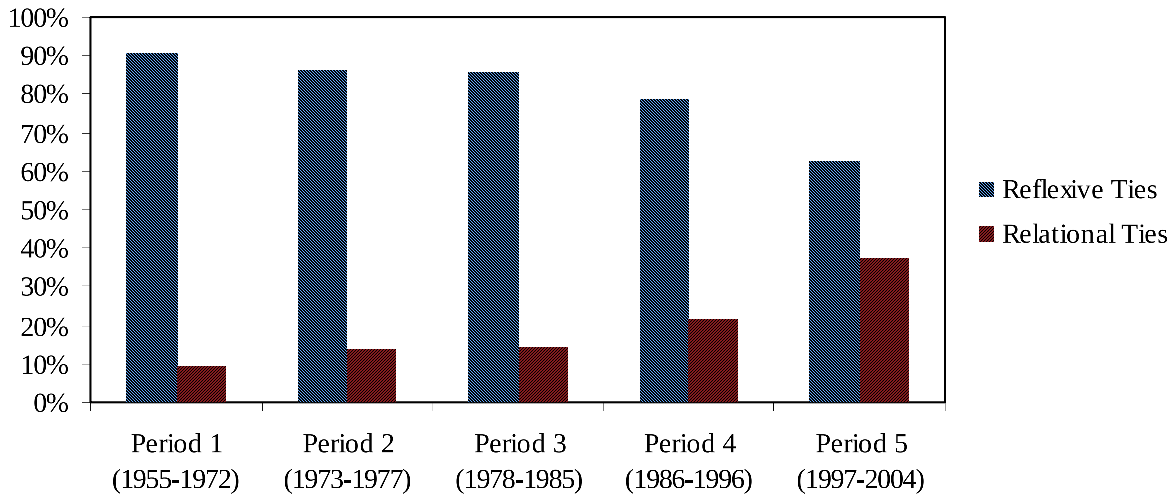

Figure 75. Reflexive and relational affiliation-type ties among authors of SWH-relevant papers in the ASES conference dataset, 1955–2004, according to period

Figure 76 illustrates the shifting prominence of particular affiliation types in coauthoring SWH-relevant papers at the ASES conference, according to each type's share of strong and regular ties (either on both sides or only one side of a tie) in different time periods. As in the other two cases, university researchers dominate overall ties, with government and non-utility firms accounting for the next largest shares of overall ties. As in the PV case, the share of ties accounted for by universities declines somewhat over time from Period 1 (75% of all ties) to Period 5 (50%) of all ties; this is in contrast to the STE case, in which the proportion of ties accounted for by university researchers grows through Period 4, then retrenches slightly in Period 5. Note that there is a noticeable upswing in the proportion of ties in SWH-relevant papers accounted for by universities in Period 4 (72%) that goes against the overall declining trend. This fact, when combined with a similar drop in the proportion of ties held by non-utility firms in Period 4 which goes against a general increasing trend for these firms over time, points to the influence of a particularly small U.S. market for SWH technologies during 1993–1997. Government authors maintain a relatively stable proportion of ties throughout 1955–2004, ranging between 14% and 19% of all ties.

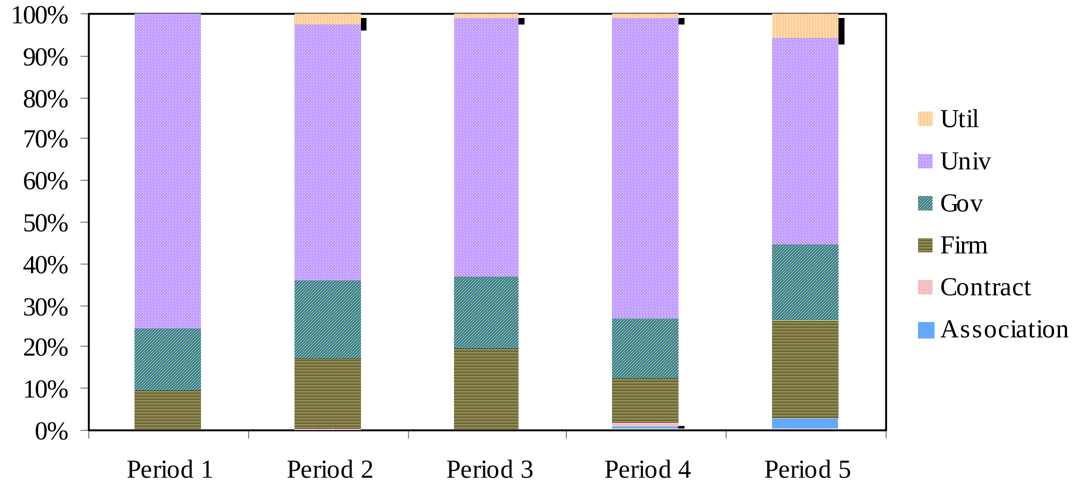

Figure 76. Strong and regular affiliation-type ties on SWH-relevant papers in the ASES conference dataset, 1955–2004, according to period

4.5. Experience Curves

Quantitative modeling of "experience curves" has become an increasingly common method of representing endogenous technical change in long-term integrated assessment models used for energy and environmental policy analysis. This section focuses on quantifying the outcomes of innovation in SWH technology by developing experience curves, which relate improvements in the cost or performance of a technology to the cumulative production of that technology. Experience curves are based on an organizational learning curve, the classical formula for which is given below.[95]

$$y_i = a{x_i}^{-b}$$

where:

y = the number of labor hours required to produce the ith unit
a = the number of labor hours required to produce the first unit
x = the cumulative number of units produced through time period i
b = the learning rate
i = a time subscript

The x-variable in this equation is a proxy for knowledge acquired through production. It is computed by summing the total units of output produced from the start of production up to, but not including, the current year (this is because of the standard assumption that experience acquired over the course of a given year will not be reflected in technical improvements in the year the experience is gained). In the SWH case, the "output" considered is the estimated cumulative megawatts of electrical thermal energy capacity (MWth) produced. This estimate was derived by converting data on thousands of square feet of medium-temperature collectors installed in the United States into square meters and then multiplying that by an assumption of 0.7 kW of thermal energy output per

[95] For a comprehensive review of organizational learning curves, see Argote (1999).

square meter of panel. This assumption was derived from IEA data on glazed and evacuated tube collectors. The y-variable in the experience curve equation is represented by capital cost data from 1973–2004 (prices are used as the measure of costs, and are given in constant 2004 dollars).[96] Capital cost data was originally obtained in units of price per system. Figure 77 depicts the experience curve—on a log-log scale—regarding the price of SWH systems as cumulative capacity (lagged by one year) increases. The main sources used in constructing this figure are: CEC (1986); Hansen and Tennant (1988); Larson, Vignola et al. (1992); and Richmond, Still et al. (2003).

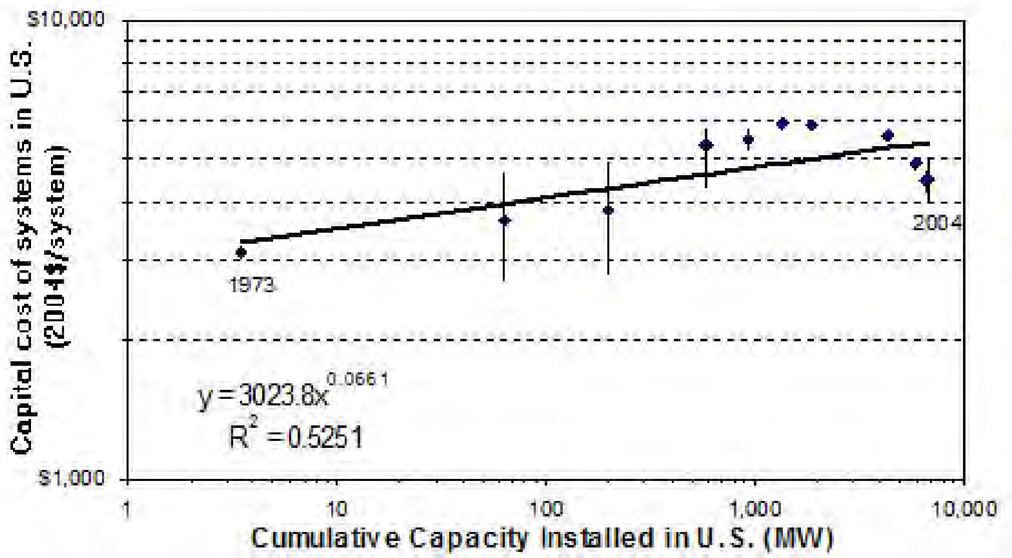

Figure 77. Experience curve for the capital cost of SWH systems in the U.S., as measured in prices

The line shown in Figure 77 is the best-fit of a power function relating the x- and y-variables; at 0.53, the goodness-of-fit is not strong. The parameter b (0.07) in the equation—the learning rate—translates into a progress ratio of $2^{0.07}$, or 1.05.[97] This means that as cumulative output doubles, the SWH system cost increases to 105% of its original level, in contrast to the cost declines exhibited in the PV and STE cases (Dutton and Thomas 1984). Although this fits with the expert interviews, which predicted increasing prices due to increases in the costs of materials (mostly steel and glass) as well as labor, uncertainty in the energy conversion efficiency factor used here ($0.7kW/m^2$) may increase the uncertainty in the slope of the curve shown in the figure.

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[96] It proved to be too difficult to construct an experience curve for a performance metric in SWH. Lifetime was the y-variable with the most promise, but data was too difficult to obtain. In interviews, experts explained that in a large number of cases, SWH units had stopped operating and owners were not aware of the fact. This, plus the distributed nature of the technology, meant that there was no consistent record of system lifetimes.

[97] The numbers derived from the equation in Figure 77 are presented in the text of this section to the second decimal point.

5.0 Discussion

The previous chapters have introduced the case technologies considered in this analysis, chronicled the history of government actions to intervene in support of these technologies, and provided brief overviews of the market developments and major innovations that occurred in the development of each technology. They also laid out the results of analyses of inventive activity using patenting activity as a metric, knowledge transfer activity using conference proceedings as a dataset, and experience curves considering the outcomes of innovation via metrics of performance and cost improvements. This chapter will highlight some of the major lessons learned from each technology case for future policy efforts to support new climate-neutral technologies, as well as some insights into the use of experience curves to model the future of climate-neutral technologies. As in the previous chapter, the results of expert interviews will be incorporated into the discussion.

5.1. Photovoltaic Cells

Since the first commercial cell was introduced, PV cells have improved considerably: costs have declined by a factor of 100 since the 1950s and the electrical efficiency of commercial cells has doubled since the 1970s. Yet the technology remains expensive relative to both conventional power generation and renewables such as wind and STE technology. With the exception of a few niches, diffusion has been trivial; worldwide cumulative installed capacity amounts to the equivalent of a few large coal-fired plants. Still, with production growing at 40% per year and continuing cost reductions, interest in future innovation in the technology is strong and governments around the world, including California, are actively engaged in supporting invention and diffusion in PV cells.

Three observations stand out about the effect of policy on innovation in PV cells. First, R&D spending has been important to PV development. Second, the combination of R&D and demand-side policies has resulted in a shift in inventive activity away from the United States and toward Japanese inventors. Third, learning-by-doing by system installers may be an important opportunity for PV cost reduction.

Support for the first of these findings primarily comes from rankings of the importance of various government actions in support of PV cells (see Figure 20). Experts ranked the 1974 Japanese R&D program (the “Sunshine Project”) second (despite its initial focus on STE R&D – see Figure 3) and U.S. federal R&D efforts between 1950 and 2005 fourth on the list they were given of seventeen government actions in support of PV that occurred between 1970 and 2005.[98] The late 1970s, when U.S. research and development was at its highest and there was virtually no diffusion of terrestrial PV, also corresponds with the largest improvements in the efficiency of commercial modules.

Note that more recent government actions have focused on the diffusion aspect of the innovation process in PV cells and have involved expectations that “learning-by-doing,”

[98] These rankings for R&D programs are higher than the rankings for R&D in STE and SWH.

or post-adoption innovative activity, and economies of scale will lead to cost reductions and performance improvements in PV. Experts ranked German, Japanese, and California actions in the 1990s and 2000s, which supported the deployment of PV cells through buydown rebates and other subsidies, first, third, and fifth, respectively, in their importance to supporting innovation in PV cells.[99] These programs are credited with encouraging the industry to grow and become more competitive, a development that is explicitly linked to innovation. The German 1,000 Roofs program was funded by the German Federal Research Ministry and the Japanese Residential Monitoring Photovoltaic Power Generating Systems program included reporting on system performance in return for subsidies. In today's discussions about California's Million Solar Roofs Program, expectations about technology improvements accompanying diffusion are used in part to justify the program.

Support for the second major observation above, that a combination of R&D and demand-side policies has resulted in a shift in inventive activity away from the United States, which has not significantly funded technological diffusion, and toward Japanese inventors, comes from patenting activity (see Figure 24). This observation raises the possibility that a similar set of incentives in the United States might drive invention by U.S. firms, bringing with it complementary economic benefits. There is both reason to believe this might happen and reason to disbelieve it, based on other experiences. One reason to believe it is that the United States has a strong patenting position and technological know-how because of its history with PV cell technology. In addition, the California experience supporting wind power, PV, STE, and SWH hints at an economic value to clean energy technology leadership. Although the full extent of the value to California of this leadership role is unclear, patent analyses indicate that California is capturing a greater share of intellectual property in these industries—18.1% of the patents in wind, 14.2% of the patents in SWH, 22.9% of the patents in STE, and 14.5% of the patents in PV—than in the patent system as a whole (8.7%). One reason to disbelieve this proposition, however, is that the German government has had in place a similar set of policies in support of R&D—Germany has the highest R&D spending as normalized against GDP of the three nations (see Figure 6)—and diffusion for about as long as Japan (Germany has had diffusion policies longer, while Japan has had R&D support longer), yet has a much weaker patent position. It is possible that that Japan's leadership of the world PV market has become so pronounced that it will not be possible for U.S. firms to gain significant market share.

Support for the third observation—that learning-by-doing by system installers may be an important opportunity for PV cost reduction—comes from discussion with experts and observation of costs. Photovoltaic installations are highly site-specific, and costs reflect that, ranging from 1–2 $/watt (W). This suggests that there is a large opportunity for

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[99] Although Figure 20 lists the Japanese "New Sunshine Project (declining rebates)," it is using a different name to refer to the Residential Monitoring Photovoltaic Power Generating Systems program, which is also known by some as the 70,000 Solar Roofs program. The New Sunshine Project itself was a broad initiative that primarily focused on R&D support, but as other Japanese measures were introduced in conjunction with it, many observers simply refer to various incentives using the New Sunshine Project name.

learning-by-doing by system installers (as there was in the case of SWH). Diffusion policies for PV have the potential of establishing a situation in which that learning-by-doing might occur.

But there are at least two cautionary tales evident from this report. One is the phenomenon of "solar profiteers" that enter a subsidized market to exploit it and then get out, leaving consumers high-and-dry (see SWH in California in the early 1980s and San Diego in the late 1970s). A second is the "white-elephant" PV system which costs as much as the rebates will allow. Giving rebates to consumers for the purchase of PV systems increases consumers' overall willingness-to-pay, since the consumer only has to pay a portion of the system price. The subsidies therefore have the effect of shifting the demand curve for PV systems upwards. This theoretical observation is supported, although not confirmed, by recent market data. For example, the prices of installed PV systems in California increased in 2001 when buy-down rebates were increased to $4.50/W. Similarly, PV prices in Germany have increased in the past few years as the federal "Renewable Energy Law" has guaranteed tariffs of greater than 50₵/kWh. In both of these cases, the prices of installed systems rose while the cost to produce the underlying components declined. It is important for policy-makers to consider whether the benefit to society is worth the subsidization of a technology when the prices that individuals face in their decision to adopt and the prices that society faces differ.

To avoid these problems, subsidies should either pay for performance (¢/kWh) or be based on verification of operation (verification programs should be carefully constructed in order to avoid some of the pitfalls of the SWH example). In addition, the current state of licensing of solar installers should be scrutinized in light of these concerns (considerable improvements have occurred since the 1980s SWH example, however).

5.2. Solar Thermal Electric Power

Government actions have influenced the development of STE power technology at all stages of the innovation process, from federal R&D in the 1970s that established heliostat design (a fundamental STE enabling technology) to inducing a surge in orders for new construction planned for 2006 and 2007. Perhaps most notably, government actions have facilitated incremental innovations in commercially installed technology that resulted in significant operating and maintenance cost reductions. Not a complete success, government actions have at times been a barrier to the diffusion of STE technologies. In addition, government actions in support of STE do not appear to have stimulated as much (or as diverse) public knowledge transfer as in the other two cases, at least as measured by the information made public in patents and in papers in the ASES conference dataset.

According to experts and the literature, the most impressive innovations in STE technology have been the cost-reducing and performance-enhancing improvements in the nine SEGS units built by Luz International, Inc., in California with roughly a billion dollars in private investor funds. From the time the first SEGS plant was built in 1984 to the time the last was built in 1990: capital costs of new plants fell by 45%; the projected cost of electricity at the time of construction dropped by nearly two-thirds (see Figure 43); O&M costs fell by 44%; and electrical conversion efficiency increased by 28% (the first plants had efficiencies below 30%, while the last plants had efficiencies of

38%)(Lotker 1991). According to expert interviews, other important innovations that emerged from the early SEGS plants included advances in improving field configuration, the development of steam reheating, and all the little innovations involved in the move to larger plants. Finally, capacity factor increased with improved maintenance of existing units by operators; for example, the number of pump failures per year decreased from over 100 in the early 1990s to less than 10 by the late 1990s. Identifying and codifying these improvements for use in other installations was a crucial function of federal R&D in STE, according to experts interviewed for this report.

Experts state that three government actions were crucial for these improvements to occur. First, the 1978 PURPA legislation enabled private firms to sell electricity to utilities. Second, California's standard offer contracts—especially the 1983–1985 interim Standard Offer Number 4 (ISO4) contract which essentially guaranteed an effective tariff of 12¢/kWh for ten years—provided some assurance to those firms of future earnings. Third, collaborative R&D between Sandia National Laboratories and the private firm, Luz, had the goal of identifying opportunities for O&M improvements in the SEGS plants. The implementation of these targeted improvements, combined with learning-by-doing and learning-by-using derived from running the plants for several years, is credited with primary responsibility for the dramatic improvements listed above.

For all these successes, it is noteworthy that the diffusion of STE overall has been so limited, with total installed capacity today two orders of magnitude less than wind power. Unfortunately, policy has been an important barrier to increased diffusion of the technology and any corresponding innovative improvements in costs and performance. For example, the limitation on maximum plant size in the PURPA regulations almost certainly hindered efforts at cost reductions, as plants were not built at their optimal scale, which experts state is about 200 MW. In addition, the large investments (> $100 m) needed to build STE plants fell afoul of utility deregulation and a 1995 FERC ruling, which forced STE plants to compete with advanced conventional generating technologies such as highly efficient natural gas-fired combined cycle gas turbine plants, based purely on the value of the private good of electricity produced rather than on any environmental benefits. But what policy taketh away, it also giveth. As a result of renewable portfolio standards in different states, especially those with solar set-asides, and policy efforts in other countries, dozens of new commercial plants are scheduled for completion in the next few years in Nevada, Arizona, Spain, and elsewhere, employing the same basic technologies as the SEGS plants and the federal demonstration plants.

Finally, the development of STE technologies appears to not be benefiting from public knowledge transfer, at least according to the metrics of patenting activity, STE-relevant papers in the ASES conference dataset, and direct research contribution on those papers from the diverse approaches and perspectives represented by cross-affiliation type relational ties between authors.[100] Despite significant innovation in the technology,

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[100] In theory, a patent rewards an inventor for investing in inventive activity with a temporary monopoly right for the commercialization of the resulting invention. The societal reward for granting this monopoly right is the enhancement of the public good of knowledge from which new discoveries and innovations

patenting activity in STE is measured on a scale of 40 per year, while patenting activity in PV and SWH is measured on scales of 250 per year.[101] Similarly, the average number of STE-relevant papers in the ASES conference dataset is only 102, in contrast with 184 for PV and 219 for SWH. And relational ties amongst authors of STE-relevant papers showed a declining trend through the second (1974–1981, 19%) and third (1982–1992, 10%) periods as the market for STE grew; this is in contrast to an increasing trend in PV in those periods.[102] In addition, experts commented independently on the lack of patenting activity and conference participation by Luz. "For whatever reason, Luz had very few patents on what they were doing," according to one expert, and according to another, "industry guys rarely publish, [they are] worried about stolen ideas."

The implication of this for policy-makers is that if government is interested in supporting innovation in a particular technology, it should play an active role in making sure that diverse pathways for knowledge transfer in that technology are not just available, but used. In the STE case, as noted above, federal R&D played a crucial role in identifying and codifying the improvements made in the SEGS plants for use in other installations, although it is an open question whether it codified the sort of tacit knowledge that facility operators develop when learning-by-doing occurs within a plant (see Taylor [2001] for the importance of tacit knowledge developed by pollution control operators in coal-fired power plants). There is little doubt from the innovation literature that more diverse pathways for knowledge exchange advance innovation (for an example, consider "open source" code), but many firms play their innovation cards "close to the chest" out of proprietary concerns. This tension is particularly troubling in technologies with large public good characteristics like clean energy technologies.

5.3. Solar Water Heating

Solar water heating technology experienced a burst of innovative activity in the late 1970s and early-1980s. Inventive activity was intense, the technology improved, and diffusion of units into the market was rapid and substantial. However, in the mid-1980s this burst of activity ended as rapidly as it began. Since then, SWH innovation in the United States has been stagnant, with only a tiny market served by a few small firms. Government actions played a major role in causing the boom, the bust, and the long period of stagnation.

Three observations stand out about the effect of policy on innovation in SWH technology. First, this rapid and brief diffusion was correlated with government actions. Second, the innovations considered most important by experts related more to learning-by-doing in the installation of systems than innovations in SWH technology per se; experts believe that these innovations were not particularly rapid, in part due to the

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draw.

[101] For additional comparison, similar datasets of patenting activity derived in other work by the author are measured on scales of: 90 for flue gas desulfurization for coal-fired power plants; 25 for selective catalytic reduction technology for gas-fired power plants, and 70 for wind power (Taylor 2001).

[102] SWH did not reflect a trend between the first and third periods.

implications of policy failures on markets for SWH and on knowledge workers employed in SWH. Third, past policy failures have made it difficult for new efforts to take hold in creating markets in the United States for SWH, despite the cost-competitiveness, reliability, and GHG advantages of this technology.

Despite the fact that patenting activity surged at the same time as the commercial market for SWH (see Figure 66 and Table 22), expert interviews suggest that these patents were not of high quality and that there has been little improvement in the technology since a few important innovations in the early 1970s, such as selective coatings, which emerged from the early federal R&D program. For example, experts pointed to the proliferation of exotic designs during the era of government subsidies that were eligible for patents and successfully differentiated the product in a crowded market, but which ultimately did not improve the performance of the systems. In addition, experts explained that there has been relatively little cost reducing or performance enhancing change in the design of new systems. This is supported in the experience curve derived for this report, which suggests that the cost of systems has actually increased slightly over time, driven more by changes in materials and labor costs than by technical improvements (see Figure 77).

The performance of *systems* has improved, however. Recent systems have overcome many of the problems that developed in the early SWH systems with age, such as freezing, leaking, and light-induced materials degradation. Experts attribute these improvements to learning-by-doing by system installers during the surge in SWH diffusion in the early 1980s; this is an important reminder that good firms, not just solar profiteers, were on the scene during this boom. Several experts emphasized the role of the conclusion of the CPUC Demonstration Project and the expiration of solar tax credits in causing these lessons to be lost, rather than codified and retained, amidst the subsequent decimation of the industry. One SWH company veteran interviewed called this the “tragedy of 1985.”

There are several policy implications from the problems incurred in the boom and bust phenomenon in SWH technology. First, there is an inherent danger in designing policies that provide incentives for installation rather than performance. The boom in the diffusion of SWH systems had a much smaller impact in offsetting large amounts of natural gas and electricity for heating water, because many of the systems did not work well and were abandoned within a few years (some claim that half of the installed systems were no longer functioning after five years). While an incentive designed purely to reward BTUs-saved may be prohibitively difficult to implement, a capital cost incentive can be made contingent on verification of systems performance. This combination has proved to be highly effective in Hawaii, where each system undergoes an inspection that costs less than $50 to conduct.

Second, SWH demonstrates the adverse effects of allowing the expiration of policies to occur suddenly and prematurely. If the best outcome of the boom in SWH diffusion was the inducement of learning-by-doing and the solving of technical problems in system installation, the worst was the loss of that knowledge over later years as companies went bankrupt and installers switched to other businesses. Little attention has been paid to how to preserve and share the lessons learned from the important experiences installers had at that time, and these lessons may now need to be re-learned.

Other lessons that may need to be relearned include those learned in evaluations of the CPUC Demonstration Project in the early 1980s. As seen in Gigi Coe's analysis of this program, summarized in part in the introduction to this report, administrative capacity can be a major issue in undercutting smart policy design and implementation. This third lesson from the SWH case may have implications for the implementation of AB32 by the California Air Resources Board, which has traditionally led the nation in terms of vehicle standards but has not been particularly active in the electricity sector, which is the sector most affected by this GHG policy. One of Coe's observations of the SWH Demonstration Project also appears relevant today to the CPUC Million Solar Roof Program for PV. That is the conclusion by the then-CPUC President Leonard Grimes that "regulatory agencies such as the CPUC are not appropriate vehicles for instituting" such programs as the Demonstration Project (Coe 1985).

A fourth policy implication of the SWH case is that the technical perception of unreliability is problematic for diffusion of an emerging technology and policies to spur diffusion in that technology, particularly if the audience familiar with the reliability problems is large. An example of this is provided in a comparison between early flue gas desulfurization (FGD) systems for coal-fired power plants, a centralized pollution control technology with reliability problems in the 1970s, to early SWH systems, a distributed technology with reliability problems in the 1980s (see Taylor [2001] for more information on FGD). In the case of FGD, unreliability led to litigation and was an important factor behind setting pollution control standards for a complementary pollutant at relatively low levels, but FGD technology continued to mature and be supported by public R&D and repeated demand-pull instruments. In the case of SWH, on the other hand, many of the systems did not work well and were abandoned within a few years. Despite technical improvements that overcame these early problems, the perception of SWH as technically unreliable killed U.S. demand for the technology for the last twenty years, and persists to some extent among both policy makers and consumers (this can be seen in the development of California's Million Solar Roofs program in 2006, for example).

Finally, a fifth policy implication from the SWH case is that policy intermittency and uncertainty undercuts innovation, and subsidies have been particularly unstable demand signals to innovators in the past (the evidence for this also comes from the wind power case). Thus, subsidies may be best to avoid for the purposes of supporting innovation unless they can be guaranteed to last over at least modest timeframes. One innovator interviewed in this research made a specific request on this subject, namely that for planning purposes, he would "rather have a lower rebate, say 15%, guaranteed for 5 years or more, than a large rebate, even more than 40%, that might last only a year or two."

5.4. Implications for Models

This research indicates that government actions have played an important role in the innovation process in these three solar energy technologies. The improvements in some of these technologies have been substantial. As a result of this, it is important that energy supply models that take technological innovation into account in forecasting GHG emissions and mitigation costs begin to characterize the influence of government actions on innovation. Although further research will be needed to establish the connections between observed characteristics and the underlying mechanisms by which government actions provide stimulus for technology improvement, the accuracy and impact on decision makers of energy supply models can only be enhanced by this more sophisticated treatment of technological change.

As a final note, the analyses in this report make it clear that it is not enough simply to plug a pre-determined experience curve progress ratio into a model, say at a level approaching 80%.[103] Although experience curves derived in previous cases cluster nicely in a small range of progress ratios (as seen in Figure 78 below), this is not true in the cases of PV, STE, and SWH (as seen in Figure 79).

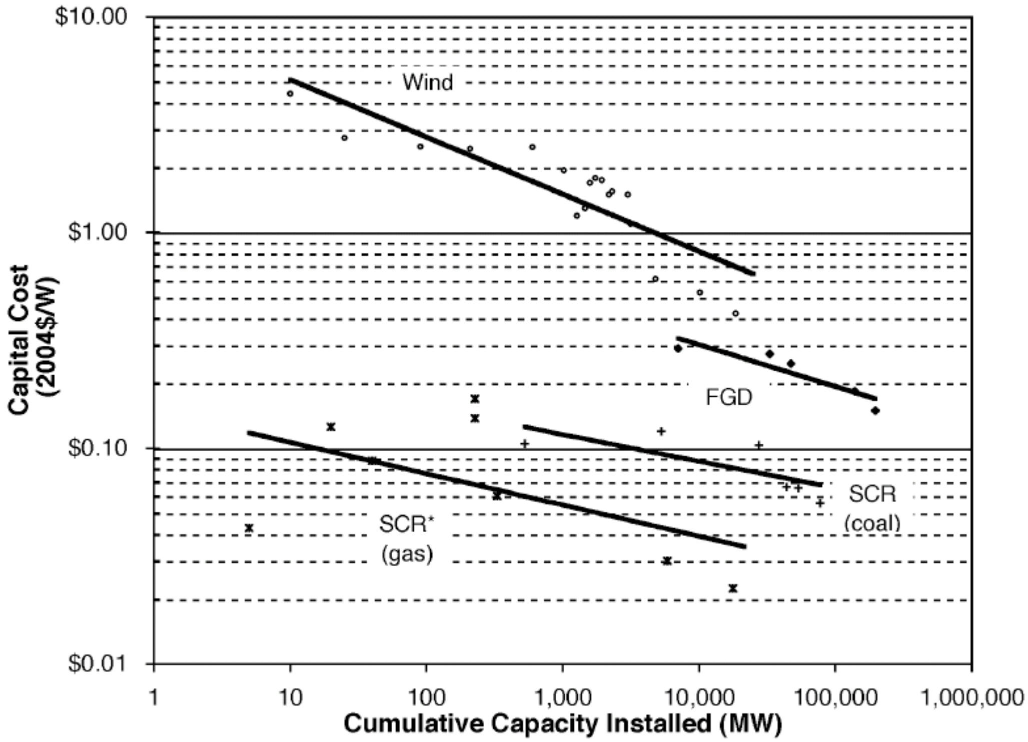

Figure 78. Experience curves derived in previous cases

Source: (Taylor 2006)

[103] Recall that this means that as cumulative output doubles, costs or performance attributes improve to some percentage of original levels. This percentage is the progress ratio; the most frequently observed progress ratio in such industries as electronics, machine tools, papermaking, aircraft, steel, and automobiles, which is 80% (Dutton and Thomas 1984).

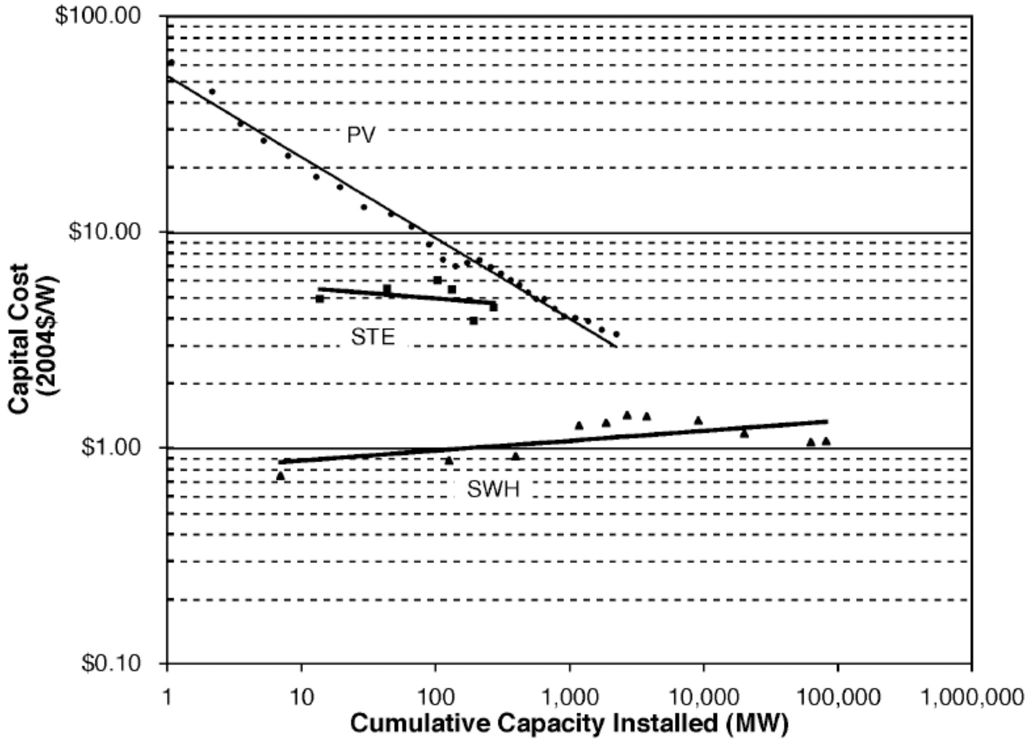

Figure 79. Experience curves derived in PV, STE, and SWH

6.0 References

Allen, T. (2005). “Legislation.” Retrieved August 16, 2006, from www.solarschoolhouse.org/legislation.html.

Argote, L. (1999). *Organizational Learning: Creating, Retaining, and Transferring Knowledge.* Norwell, Mass., Kluwer Academic Publishers.

AZSC (2006). How a PV Cell Works. Arizona Solar Center. www.azsolarcenter.com/technology/electric.html.

Badr, M., and R. Benjamin (2003). *Comparative Cost of California Central Station Electricity Generation Technologies.* Final Staff Report 100-03-001F, California Energy Commission, Electricity Analysis Office.

Beattie, D. E., Ed. (1997). *History and Overview of Solar Heat Technologies.* Solar Heat Technologies: Fundamentals and Applications. Cambridge, Mass., MIT Press.

Bemis, G., and J. Allen (2005). *Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2002 Update.* Sacramento, California Energy Commission.

Bereny, J. (1977). *Survey of the Emerging Solar Energy Industry.* F. de. Winter, editor. Solar Energy Information Services (San Mateo, Cal.).

Berman, D. M., and J. T. O’Connor (1996). *Who Owns the Sun? People, Politics, and the Struggle for a Solar Economy.* Vermont, Chelsea Green Publishing Co.

Block, D., and J. Harrison (1997). Solar water heating: A question and answer primer. Florida Solar Energy Center (FSEC).

Brakmann, G., R. Aringhoff, et al. (2005). *Concentrating Solar Thermal Power – Now! Exploiting the Heat from the Sun to Combat Climate Change.* Hamburg, Germany, European Solar Thermal Industry Association, IEA SolarPACES, Greenpeace International.

Brechlin, U., O. Pilgaard, et al. (2003). *Sun in Action II – A Solar Thermal Strategy for Europe.* The Solar Thermal Sector Country by Country, 21 National Reports. Brussels, European Solar Thermal Industry Federation.

Bush, V. (1945). *Science the Endless Frontier: A Report to the President on a Program for Postwar Scientific Research.* Washington, D.C., National Science Foundation.

Butti, K., and J. Perlin (1980). *A Golden Thread: 2500 Years of Solar Architecture and Technology.* Palo Alto, Cal., Cheshire Books.

CEC (1986). *Solar and Wind Technology Tax Incentive Impact Analysis.* Sacramento, Cal., California Energy Commission.

CEC (2005). Annual project activity report to the legislature, Renewable Energy Program. Sacramento, Cal., CEC: 55.

CEC. (2006, August 8, 2006). “California State Tax Credits for Solar & Wind Systems Completed on or Before December 31, 2005.” Consumer Energy Center. Retrieved August 22, 2006, from www.consumerenergycenter.org/erprebate/new_info.html.

Chapin, D. M., C. S. Fuller, and G. L. Pearson. (1954). “A New Silicon P-N Junction Photocell for Converting Solar Radiation into Electrical Power.” *Journal of Applied Physics* 25: 676–677.

Clarke, N., and M. Riba (1998). Patent Information for Technology Foresight. Vienna, Austria, European Patent Office.

Coe, G. (1985). California's Experience in Promoting Renewable Energy Development. *State Energy Policy: Current Issues, Future Directions.* S. W. Sawyer and J. R. Armstrong. Boulder, Colorado, Westview Press: 193–211.

Cohen, G. E., D. W. Kearney, et al. (1999). *Final Report on the Operation and Maintenance Improvement Program for Concentrating Solar Power Plants.* Albuquerque, New Mexico, Sandia National Laboratories.

Cohen, W., and J. Levin (1989). Empirical Studies of Innovation and Market Structure. *Handbook of Industrial Organization.* R. Schmalensee and R. D. Willig. Amsterdam, Elsevier Publishers, B.V. 2: 1059–1107.

Del Chiaro, B. (2006). "California Passes Million Solar Roofs Bill." *Environment California* August 13, 2006.

DOE. (2006, 01/05/2006). "Solar Timeline." Retrieved July 13, 2006, from www1.eere.energy.gov/solar/solar_timeline.html.

Dutton, J. E., and A. Thomas (1984). "Treating progress functions as a managerial opportunity." *Academy of Management Review* 9: 235–47.

EERE (2006a). A Consumer's Guide to Energy Efficiency and Renewable Energy. www.eere.energy.gov/consumer/.

EERE (2006b). Solar Hot Water and Space Heating & Cooling.

EIA (2001). *Annual Energy Review.*

EIA (2005). *Policies to Promote Non-Hydro Renewable Energy in the United States and Selected Countries.* Washington, D.C., Energy Information Administration, U.S. Department of Energy.

EIA (2006a). *Annual Energy Review 2006.* DOE EIA.

EIA (2006b). Solar Thermal and Photovoltaic Collector Manufacturing Activities 2005, DOE EIA.

Enermodal (1999). *Cost Reduction Study for Solar Thermal Power Plants.* Washington, D.C., World Bank.

Fukada, T. (2001). "Japan Plans to Launch Solar Power Station in Space by 2040." SpaceDaily.

Galloway, J. H. (2000). *Policies and Programs to Support Solar Water Heating Systems: An Analysis with a Case Study of a Municipal Solar Utility in Santa Clara, California.* Energy and Resources Group. Berkeley, University of California, Berkeley. M.S.: 85.

Gazit, C. (1999). "Meltdown at Three Mile Island: Timeline of Nuclear Energy, 1942–1959." *The American Experience,* from www.pbs.org/wgbh/amex/three/timeline/index.html.

Gielecki, M., F. Mayes, et al. (2001). *Incentives, Mandates, and Government Programs for Promoting Renewable Energy*. Washington, D.C., Energy Information Administration.

Griliches, Z. (1990). "Patent Statistics as Economic Indicators: A Survey." *Journal of Economic Literature* 28 (December 1990): 1661–1707.

Griliches, Z. (1992). "The Search for R&D Spillovers." *Scandinavian Journal of Economics* 94: S29–47.

Grosskreutz, J. C. (1996). High-Temperature Technologies. *Implementation of Solar Thermal Technology.* R. W. Larson and R. E. West. Cambridge, Mass., Massachusetts Institute of Technology. 10.

Guey-Lee, L. (1999). *Renewable energy 1998: Issues and trends*; Renewable electricity purchases: History and recent developments. Washington, D.C., U.S. Department of Energy, Energy Information Administration.

Haas, R. (2003). “Market deployment strategies for photovoltaics: An international review.” *Renewable and Sustainable Energy Reviews* 7: 271–315.

Halacy, D. S., Jr. (1973). *The Coming Age of Solar Energy, Revised Edition.* New York, Harper & Row.

Hansen, C. E., and W. L. Tennant (1988). Historical Cost Review *Economic analysis of solar thermal energy systems.* R. E. West and F. Kreith. Cambridge, Mass., MIT Press: 372–413.

Hayter, S. J., and R. L. Martin (1998). *Photovoltaics for Buildings: Cutting-Edge PV.* Golden, Colorado, National Renewable Energy Laboratory.

Hempel, L. C. (1983). The Politics of Sunshine: An Inquiry into the Origin, Growth, and Ideological Character of the Solar Energy Movement in America. Government. Claremont, California, Claremont Graduate School. PhD.

Hester, S. L., T. U. Townsend, et al. (1990). *PVUSA: Lessons learned from startup and early operation.* Photovoltaic Specialists Conference, 1990. Conference Record of the Twenty First IEEE, Kissimmee, Florida.

Hollon, J. K. (1980). Solar Energy for California’s Residential Sector: Progress, Problems, and Prospects. *Institute of Governmental Studies Research Report 80-3.* Berkeley, University of California, Berkeley.

IEA (2005). *Projected Costs of Generating Electricity – 2005 Update.* Paris, IEA: 232.

IEA. (2006). “R&D Statistics Access Database.” Retrieved June 2, 2006, 2006, from www.iea.org/rdd/eng/ReportFolders/Rfview/Explorerp.asp?CS_referer=.

IREC (2006). Database of State Incentives for Renewable Energy (DSIRE). North Carolina Solar Center.

Jager-Waldau, A. (2004). *PV Status Report 2004.* Ispra, Italy, European Commission Directorate General Joint Research Centre Institute for Environment and Sustainability.

Jevons, W. S. 1865. *The Coal Question: An inquiry concerning the progress of the nation and the probably exhaustion of our coal-mines.* London: Macmillan.

Johansson, T. B., H. Kelly, et al., Eds. (1993). *Renewable Energy: Sources for Fuels and Electricity*. Washington, D.C., Island Press.

Jones, C. I., and J. C. Williams (1998). “Measuring the Social Return to R&D.” *Quarterly Journal of Economics* 113(4): 1119–1135.

Kearney, D. W., and H. Price (2005). “Recent Advances in Parabolic Trough Solar Power Plant Technology.” *Solar Energy* American Solar Energy Society, Inc. (ASES) 16: 155–232.

Kemp, R. (1997). *Environmental Policy and Technical Change: A Comparison of the Technological Impact of Policy Instruments.* Cheltenham, Edward Elgar.

Hubbert, M. K. 1956. “Nuclear Energy and the Fossil Fuels.” Presented before the Spring Meeting of the Southern District, American Petroleum Institute, Plaza Hotel, San Antonio, Texas, March 7–9, 1956.

Kinnee, R. M. (2005). Analysis of Senate Bill 1017 (Campbell) *Staff Legislative Bill Analysis.* Sacramento, California, State Board of Equalization.

Kurokawa, K. and O. Ikki (2001). "The Japanese experiences with national PV system programmes." *Solar Energy* 70(6): 457–466.
Laird, F. N. (2001). *Solar Energy, Technology Policy, and Institutional Values.* Cambridge University Press.
Larson, R. W., F. Vignola, et al. (1992). *Economics of Solar Energy Technologies.* Boulder, Colorado, American Solar Energy Society.
Larson, R. W., and R. E. West, Eds. (1996). *Implementation of Solar Thermal Technology.* Solar Heat Technologies: Fundamentals and Applications. Cambridge, Mass., MIT Press.
Larson, R. W., and R. E. West (1996). Introduction. *Implementation of Solar Thermal Technology.* R. W. Larson and R. E. West. Cambridge, Mass., Massachusetts Institute of Technology. 10.
Lotker, M. (1991). *Barriers to Commercialization of Large-Scale Solar Electricity: Lessons Learned from the Luz Experience.* Albuquerque, New Mexico, Sandia National Laboratories.
Margolis, R. M. (2002). Understanding Technological Innovation in the Electricity Sector: The Case of Photovoltaics. Woodrow Wilson School of Public and International Affairs. Princeton, New Jersey, Princeton University. PhD.
Mariyappan, J., and D. Anderson (2001). *Thematic Review of GEF-Financed Solar Thermal Projects.* London, UK, Global Environment Facility.
Martinot, E. (2005). *Renewables 2005 Global Status Report.* Washington, D.C. The Worldwatch Institute for the REN21 Renewable Energy Policy Network.
Maycock, P. D. (1999). *The World Photovoltaic Market 1975–1998*. Warrenton, Va., PV Energy Systems, Inc.
Maycock, P. D. (2004a). *Photovoltaic Technology, Performance, and Cost 1995–2010.* Warrenton, Va., PV Energy Systems, Inc.
Maycock, P. D. (2004b). *The World Photovoltaic Market.* Warrenton, Va., PV Energy Systems, Inc.
Maycock, P. D., and W. Bower (2004). *National Survey Report of PV Power Applications in the United States.* Paris, International Energy Agency Cooperative Programme on Photovoltaic Power Systems.
Mingyuan, W. (2005). "Government Incentives to Promote Renewable Energy in the United States." *Temple Journal of Science Technology and Environmental Law* 24(2): 355–366.
Moomaw, W., A. Serchuk, et al. (1999). "Renewable Energy in a Carbon Limited World." *Advances in Solar Energy: An Annual Review of Research and Development* 13: 68–135.
Nowak, S. (2004). *Trends in Photovoltaic Applications: Survey report of selected IEA countries between 1992 and 2003.* Paris, France, International Energy Agency Photovoltaic Power Systems Programme.
NREL. (2005). "PV Manufacturing R&D History." Retrieved August 8, 2006.
OECD (2006). Annual National Accounts. Statistics, Data and Indicators. Gross Domestic Product (GDP) for OECD member countries from 1970 onwards., OECD.

Ohira, T. (2006). “Measures to Promote Renewable Energy and the Technical Challenges Involved.” S. a. T. F. Center, Japan National Institute of Science and Technology Policy 18: 98–114.

Peyton, C. (2000). “Sun May be Setting on Solar Center; State Will Close Site If It Can't Find Research Funding.” *Sacramento Bee.* Sacramento, California: B-1.

PG&E. (2006). “Self-Generation Incentive Program.” Retrieved August 17, 2006, from www.pge.com/selfgen/.

Quigley, J. M. (1991). Residential Energy Conservation Standards, Subsidies, and Public Programs. *Regulatory Choices: A Perspective on Developments in Energy Policy*. R. J. Gilbert. Berkeley, California, University of California Press.

Rader, N., and K. Bossong (1990). *The power of the states: A fifty-state survey of renewable energy.* Washington, D.C., Public Citizen, Critical Mass Energy Project.

Reece, R. 1979. *The Sun Betrayed. A Report on the Corporate Seizure of U.S. Solar Energy Development.* Cambridge, Mass.: South End Press. 234pp.

REPiS. (2003, 7/26/2004). “Charts of Cumulative U.S. Renewable Generating Capacity by Technology.” Retrieved June 5, 2006, from www.nrel.gov/repis.

Richmond, R., S. Still, et al. (2003). *Utility Success Stories in Solar Water Heating*. ASES 2003 Annual Meeting, Austin, Texas, American Solar Energy Society.

Rickerson, W. (2002, 2003). “German Electricity Feed Law Policy Overview.” Retrieved August 22, 2006, from www.wind-works.org/articles/fl_Rickerson.html.

Ristau, O. (2001). The Photovoltaic Market in Japan: Unquestioned Leadership of World Market.

Rogers, E. M. (1995). *Diffusion of Innovations.* New York, New York, Free Press.

Rosenberg, N. (1969). “The Direction of Technological Change: Inducement Mechanisms and Focusing Devices.” *Economic Development and Cultural Change* 18: 1–24.

Rubin, E. S. (2001). *Introduction to Engineering and the Environment.* New York, New York, McGraw-Hill.

Sargent & Lundy (2002). Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts. Chicago, Sargent & Lundy LLC.

Sawin, J. L. (2001). The Role of Government in the Development and Diffusion of Renewable Energy Technologies: Wind Power in the United States, California, Denmark, and Germany, 1970–2000. Fletcher School of Law and Diplomacy. Medford, Tufts University. PhD: 634.

Schaeffer, G. J., A. J. Seebregts, et al. (2004). *Learning from the Sun; Analysis of the use of experience curves for energy policy purposes: The case of photovoltaic power.* Final report of the PHOTEX project. ECN Renewable Energy in the Built Environment.

Schmoch, U., and T. Schnoring (1994). “Technological Strategies of Telecommunications Equipment Manufacturers: A Patent Analysis.” *Telecommunications Policy* 18(5): 397–413.

Schumpeter, J. (1942). *Capitalism, Socialism, and Democracy.* New York, Harper.

SEPA (1991). *TEAM-UP Final Summary Report.* Washington, D.C., Solar Electric Power Association: 47.

Sklar, S. (1990). “The Role of the Federal Government in the Commercialization of Renewable Energy Technologies.” *Annual Review of Energy* 14: 121–32.

Stoft, S. (2006). Current Gas Prices and Price History. zFacts.com.

Talbot, D., and R. E. Morgan (1981). *Power and Light: Political Strategies for the Solar Transition.* New York, The Pilgrim Press.

Taylor, M. (2001). The Influence of Government Actions on Innovative Activities in the Development of Environmental Technologies to Control Sulfur Dioxide Emissions from Stationary Sources. Engineering and Public Policy. Pittsburgh, Penn., Carnegie Mellon University. PhD.

Taylor, M. R. (2006). The Role of Technological Innovation in Meeting California’s Greenhouse Gas Emission Targets. *Managing Greenhouse Gas Emissions in California.* W. M. Hanemann and A. Farrell. Berkeley, California Climate Change Center at the University of California, Berkeley.

Taylor, M. R., E. S. Rubin, et al. (2003). “The Effect of Government Actions on Technological Innovation for SO_2 Control.” *Environmental Science and Technology* 37(20): 4527–4534.

Tester, J. W., E. M. Drake, et al. (2005). *Sustainable energy: Choosing among options.* Cambridge, Mass., MIT Press.

Thomas, H. P., S. J. Hayter, et al. (2000). PV and PV/Hybrid Products for Buildings. 16th European Photovoltaic Solar Energy Conference and Exhibition. Glasgow, Scotland, UK.

Watanabe, C. (1995). “Identification of the Role of Renewable Energy: A View from Japan’s Challenge: The New Sunshine Program.” *Renewable Energy* 6(3): 237–274.

Wiser, R. H. (1996). “Evaluating the Impacts of State Renewables Policies on Federal Tax Credit Programs.” Lawrence Berkeley National Laboratory. Berkeley, California. December.

Wiser, R., S. Pickle, et al. (1998). “Renewable energy policy and electricity restructuring: A California case study.” *Energy Policy* 26(6): 465–475.

Yamaguchi, M. (2001). “Present Status and Prospects of Photovoltaic Technologies in Japan.” *Renewable and Sustainable Energy Reviews* 5: 113–135.

Zucchet, M. J. (1995). Renewable Resource Electricity in the Changing Regulatory Environment. *Renewable Energy Annual 1995.* Washington, D.C., Energy Information Administration: xxv–xxxii.

7.0 Glossary

AEC	Atomic Energy Commission
ACRS	Accelerated Cost Recovery System
AFASE	Association for Applied Solar Energy
ASES	American Solar Energy Society
BOS	balance of system
BRPU	Biennial Resource Plan Update
CalSECDA	California Solar Energy and Conservation Development Authority
CAL SEIA	California Solar Energy Industries Association
CIS	Copper Indium Diselenide
CO_2	carbon dioxide
CPUC	California Public Utilities Commission
CSI	California Solar Initiative
DOE	U.S. Department of Energy
DPR	Domestic Policy Review
ECPA	Energy Conservation and Production Act of 1976
EFL	Electricity Feed-In Law
EPCA	Energy Policy and Conservation Act of 1975
EPACT	Energy Policy Act
EPRI	Electric Power Research Institute
ERDA	Energy Research and Development Administration
ERTA	Economic Recovery Tax Act
ETA	Energy Tax Act of 1978
ETAP	Energy Technologies Advancement Program
FEA	Federal Energy Administration
FERC	Federal Energy Regulatory Commission
FGD	flue gas desulfurization
ft^2	square foot
GHG	greenhouse gas
HUD	Department of Housing and Urban Development
IOU	investor-owned utility
IRRPOS	Interdisciplinary Research Relevant to Problems of Our Society
ISES	International Solar Energy Society
JPL	Jet Propulsion Laboratory
LCPDIPSE	Law Concerning the Promotion of Development and Introduction of Petroleum Substituting Energy
MACRS	Modified Accelerated Cost-Recovery System
MASEC	Mid-America Solar Energy Complex
METI	Japanese Ministry of Economy, Trade, and Industry
MITI	Japanese Ministry of International Trade and Industry
MSRI	Million Solar Roofs Initiative
MSU	municipal solar utility
MWe	megawatt electric
NASA	National Aeronautics and Space Administration
NASDA	Japan's National Space Development Agency
NEA	National Energy Act

NECPA	National Energy Conservation Policy Act
NEDO	New England Industrial Technology Development Organization
NESEC	Northeast Solar Energy Center
NGO	nongovernmental organization
NO_X	nitrogen oxides
NREL	National Renewable Energy Laboratory
NSF	National Science Foundation
NSF-RANN	Research Applied to National Needs Program
NSP	New Sunshine Program
OAT	Office of Appropriate Technology
OECD	Organisation for Economic Co-operation and Development
OPEC	The Organization of the Petroleum Exporting Countries
PBI	Performance-Based Incentive Program
PIER	Public Interest Energy Research
PURPA	Public Utilities Regulatory Policy Act
PV	Photovoltaic
PV:BONUS	Building Opportunities in the U.S. for Photovoltaics
PVMaT	Photovoltaic Manufacturing Technology Project
PVUSA	Photovoltaics for Utility Scale Applications
QF	qualifying facilities
RANN	Research applied to National Needs
R&D	Research and Development
RD&D	Research, Development, and Demonstration
REEETCA	Renewable Energy and Energy Efficiency Technology Competitiveness Act
REFIT	Renewable Energy Feed-In Tariff
REL	Renewable Energy Law
REPI	Renewable Energy Production Incentive
RPS	Renewable Portfolio Standard
RRTF	Renewable Resource Trust Fund
RSEC	Regional Solar Energy Center
S&L	savings and loan
SAFE-BIDCO	State Assistance Fund for Energy-California Business and Industrial Development Corporation
SCR	selective catalytic reduction
SCE	Southern California Edison
SDG&E	San Diego Gas & Electric
SEGS	Solar Energy Generating Stations
SEP	Supplemental Energy Payments
SEPA	Solar Electric Power Association
SERI	Solar Energy Research Institute
SES	Solar Energy Society
SGIP	Self-Generation Incentive Program
SMUD	Sacramento Municipal Utility District
SoCal Gas	Southern California Gas
SRCC	Solar Rating Certification Corporation

SSEC	Southern Solar Energy Center
STE	Solar Thermal Electric
SWH	Solar Water Heating
SPP	small power producers
TEAM-UP	Technology Experience to Accelerate Markets in Utility Photovoltaics
TEFRA	Tax Equity and Fiscal Responsibility Act
TIPSE	Testing and Inspection Program for Solar Equipment
UPVG	Utility Photovoltaic Group
USDA	United States Department of Agriculture
USPTO	United States Patent and Trade Office
UV	ultraviolet
W	watt
Western SUN	Western Solar Utilization Network

Appendix A.

Patent Search Methodology

Appendix A. Patent Search Methodology

A central challenge of using patenting activity as a metric of inventive activity is to identify a set of patents from the more than six million patents granted by the U.S. Patent and Trademark Office (USPTO) to serve as the dependent variable without excessive "undercounting" (including too few relevant patents) or "over counting" (including too many irrelevant ones). Based on the methodology of Taylor (2001), this report uses two approaches to patent identification which draw on two main sources of data: the USPTO patent database and an interview with the primary USPTO examiner of each set of technologies.

A.1. Class-Based Search

In the first of these approaches, the "class-based" search technique, the USPTO classes used to develop prior art—earlier patents whose claims are legally determined by the patent examiner to be closely related to the claims in the citing patent—were elicited from the patent examiner.[1] These classes were then used to generate a time-series of patents issued from 1887–2002 that was relevant to each technology. This "class-based" patent dataset is consistent for over 100 years, and thus, can be used to relate patenting trends to the timing of long-past government actions related to the technology. The tradeoff for the length of this dataset is that it is less certain with respect to undercounting and over-counting than are other approaches to patent analysis, such as the "abstract-based" search method described below.

The following methodology was used for conducting patent searches:

1. Identify possible classes that are relevant to the technology categories defined by the researchers.
2. Identify appropriate patent examiner to interview using initial searches. Which examiner(s) appear most frequently for recently granted patents?
3. Interview examiner(s).
    a. Telephone interviews were conducted with the following patent examiners: Alan Diamond (11/30/04), T. Denion (12/15/04), H. Nguyen (12/17/04), Carl Price (2/14/05).
    b. The following questions were asked:
        - Are these classes correct?
        - Are there likely to be patents in these classes that do not fit into our technology categorization?
        - Which other classes would be appropriate to search in?

[1] Patents are assigned to a "primary class" and can be also assigned to one or many secondary, or "cross classes."

- What keywords do you use when searching for prior art in these technology areas?

Samples of patents in classes that the examiner suggested were read to gauge whether these classes are appropriate to the study's definition of the technology. This study's researchers then compiled a final list of class/subclass combinations with which to search. Those classes and their definitions are described in the sections below.

A.1.1. PV

U.S. Patent and Trademark Office Examiner Alan Diamond was interviewed on 11/30/04. He indicated that the main PV class is 136. He suggested a series of sub-classes to use. He also suggested several subclasses that were adjacent to these subclasses but which he pointed out were not relevant to PV; these subclasses were excluded from the search. From this conversation, the research team devised the following search string, which was used to search the USPTO database:

((ccl/136/25$ or ccl/136/26$ or ccl/136/24$) andnot (ccl/136/240 or ccl/136/241 or ccl/136/242))

This search yielded 4,386 patents. The definitions of each patent class and subclass used are as follows:[2]

CLASS 136, BATTERIES: THERMOELECTRIC AND PHOTOELECTRIC
This class is the generic class for primary, secondary, and thermal batteries. It includes the structure of the generator or battery itself, the elements thereof, the methods of preparation, operation, and details, and accessories not provided for in other classes.

243 PHOTOELECTRIC:
Device which generates an electric potential upon exposure to light, by the direct conversion of the light to electrical energy—that is, photovoltaic.

(1) Note. Similar structures may be disclosed as having other functions, e.g., rectifying, photoconductive, etc., and some of these photoelectric devices may be disclosed as having several functions. A patent which discloses or claims only a photovoltaic use will be placed here. A patent which claims other uses or which is claimed generically will be placed in another pertinent class, e.g., Class 250, Radiant Energy, or Class 257, Active Solid-State Devices (e.g., Transistors, Solid-State Diodes).

244 Panel or array:
A photoelectric cell combined with (a) at least one other photoelectric cell, or (b) a different electric generating means (e.g., galvanic), or (c) distinct perfecting means for the photocell (e.g., cooling means).

245 Lightweight and collapsible or foldable:

[2] USPTO. (2005). "U.S. Patent and Trademark Office: Manual of Patent Classification." Retrieved January, 2005, from http://www.uspto.gov/web/patents/classification/.

Device which includes means to associate various parts or elements in a first compact arrangement for storage and/or transport and also in a second operative arrangement for accepting radiation, said device also utilizing materials and structures designed to decrease the mass or gravitational attraction.

246 With concentrator, orientator, reflector, or cooling means:
Device which includes means to intensify, direct, or redirect light rays with respect to the active elements or which includes means to lower the temperature of the device.

247 Fluorescent concentrator:
Device in which the light energy is absorbed and re-emitted at a different wave length by the concentrator.

248 Hybrid conversion system:
Device which includes at least one other source of electric energy (e.g., galvanic, etc.) or means to utilize heat energy.

(1) Note. Using the sun's rays for both heat and electric power is a hybrid system.

249 Monolithic semiconductor:
Device in which the same semiconductor layer is common to two or more individual cells.

250 Particulate or spherical semiconductor:
Device in which the semiconductor exists is a state of fine subdivision or is in the shape of a sphere.

251 Encapsulated or with housing:
Device in which the photocells are embedded in one fluent, but now solidified material or are contained within a framework.

252 Cell:
Device directed to the details of an individual cell and/or associated perfecting or enabling elements.

253 Radioactive, ionic, or thermo photo:
Photocell in which the light which generates the photovoltaic effect is produced by radio activity, ions, or heat (e.g., scintillation or incandescence, etc.).

254 Photoemissive, capacitive, magnetic, or ferroelectric:
Device in which the light (a) causes emission of electrons from a cathode, (b) alters the capacitance, (c) acts in a magnetic field, or (d) utilizes the ferroelectric property of said device.

255 Shottky, graded doping, plural junction or special junction geometry:
Device which includes a free metal semiconductor junction, more than one junction or a junction claimed in terms or specific shape or dimensions.

256	Contact, coating, or surface geometry:
Device in which the claims recite the material, size or configuration of a contact, a covering film or the surface of the photocell.

257	Luminescent layer or optical filter:
Device in which a coating has the property of absorbing light of selected frequency or of re-emitting absorbed light.

258	Polycrystalline or amorphous semiconductor:
Device in which the semiconductor material is claimed or solely disclosed as being polycrystalline or amorphous.

259	With concentrator, housing, cooling means, or encapsulated:
Device in which the photocell is embedded in once fluid, but now solidified, material or is contained within a framework or includes means to lower the temperature of the device or means to intensify the light.

260	Cadmium containing:
Device in which an active layer includes a cadmium compound.

261	Silicon or germanium containing:
Device in which an active layer includes silicon or a silicon or germanium compound.

262	Gallium containing:
Device in which an active layer includes a compound of gallium.

263	Organic active material containing:
Device in which an active layer includes a carbon compound classifiable in Class 260, Chemistry of Carbon Compounds or the Class 532 - 570 series, Organic Compounds.

264	Selenium or tellurium containing:
Device in which an active layer contains either selenium or tellurium as an element or an inorganic compound.

265	Copper, lead, or zinc containing:
Device in which an active layer includes an inorganic compound of copper, lead, or zinc.

A.1.2. STE

To devise the patent search for solar thermal electric, the research team spoke with two examiners. Thomas Denion is the head of the art unit that covers STE. Huong Nguyen is the primary examiner for subclasses 60/641.x

Mr. Denion has been an examiner at USPTO for 19 years. The research team explained the project to him, what researchers were looking for in STE, and the initial list of 7 subclasses that had been identified. He said that researchers “have the right areas” and that those “7 subclasses (60/641.8 to 60/641.15) are the right ones to be looking in.” He referred the team to Examiner Nguyen.

Mr. Nguyen also said that those 7 subclasses in 60/641.x are “the right ones to be looking at.” He said they cover three main elements of “solar thermal electric” devices:

1. solar concentrators (e.g., lenses and mirrors),
2. working fluid and heat exchangers, and
3. heat engines “usually steam turbines but sometimes Stirling engines.”

From these interviews we devised the following search string used to search the USPTO database:

(((((((CCL/60/641.8 OR CCL/60/641.9) OR CCL/60/641.10) OR CCL/60/641.11) OR CCL/60/641.12) OR CCL/60/641.13) OR CCL/60/641.14) OR CCL/60/641.15)

This search yielded 458 patents. The definitions of each patent class and subclass used are as follows:[3]

CLASS 60, POWER PLANTS
This is the residual class concerned with the driving of a load by the conversion of heat, pressure, radiant, or gravitational energy into mechanical motion. It includes a motor in combination with its energy supply or its exhaust treatment. It also includes the motors, per se, combinations of motors, and elements specialized for use in such energy conversion that are not specifically provided for elsewhere.

641.8 Solar:
Apparatus wherein the source of heat is the sun.

641.9 With distillation:
Apparatus wherein solar heat is used to heat a mixture for separating a more volatile part from at least one other part.

641.1 UTILIZING NATURAL HEAT:
Subject matter operating by means of heat evolved from natural sources, such as from the sun, air, water, earth, etc.

With elevated structure:
Apparatus in which the motor or power plant operates at least in part by energy derived either from a substance confined or constrained to move in a desired path by a significant vertically extending man-made structure (e.g., house, chimney, etc.) or from a solar heat receptor mounted on such structure.

[3] USPTO. (2005). "U.S. Patent and Trademark Office: Manual of Patent Classification." Retrieved January, 2005, from http://www.uspto.gov/web/patents/classification/.

641.12 Air is working fluid:
Apparatus wherein the substance is air.

641.13 With single state working substance:
Apparatus wherein the heat heats a substance (solid or liquid) for producing work, the substance remaining in its solid or fluid state at all times.

641.14 Gaseous:
Apparatus wherein the substance is either air or gas.

641.15 With solar concentration:
Apparatus provided with significant solar ray focusing means.

A.1.3 SWH

To devise the patent search for solar water heaters, the research team spoke with Examiner Carl Price. Before contacting him, researchers had identified that the range of subclasses 126/561 through 126/713 had many subclasses that looked appropriate. The team reviewed each of the ~100 sub-classes with Examiner Price and identified a subset that are relevant to solar water heaters. From this interview, the following string was devised and used to search the USPTO database:

(((((CCL/126/61$ OR CCL/126/62$) OR CCL/126/63$) OR CCL/126/609) OR CCL/126/640) OR CCL/126/641)

This search yielded 1765 patents. The definitions of each patent class and subclass used are as follows:[4]

CLASS 126, STOVES AND FURNACES
This class includes, generally, apparatus for the application of heat. It comprises cooking and heating stoves, hot-air furnaces, and accessories; hot-air radiators and heating drums; open liquid heaters, steaming apparatus, dampers, fireplaces, and stovepipes. It includes the fuel burner when combined with the stove or furnace structure; combinations of a particular stove or furnace structure of the type classified in this class (126) with a closed liquid heater or steam generator; liquid heaters of only the nonpressure type unless they are structurally tied to the stove or furnace or form a necessary part thereof, and grates of general use in stoves, hot-air furnaces, or boiler furnaces.

609 With auxiliary heat source for fluent medium:
Apparatus which further includes a heater other than solar to add thermal energy to the fluent medium.

610 In a tank:
. Apparatus wherein the heater is located within a storage reservoir containing the fluent medium.

[4] USPTO. (2005). "U.S. Patent and Trademark Office: Manual of Patent Classification." Retrieved January, 2005, from http://www.uspto.gov/web/patents/classification/.

611 In a heat exchanger:
Apparatus wherein the heater is located within a device that transfers heat from one fluid to another without mixture of the fluids.

612 In the collector:
. Apparatus wherein the heater is located within the enclosure for the converting means.

613 Heat pump:
. Apparatus wherein the heater is a device that has both a refrigerating mode and a heating mode, and the heating mode of the device is used as the heater for the fluent medium.

614 Fireplace:
. Apparatus wherein the heater includes structure for providing a flame within an inhabitable enclosure and which, in one condition of operation, provides visibility of the flame to inhibitants in the enclosure and heat to the fluent medium.

615 Water heater:
. Apparatus wherein the heater is a device that has an additional function of providing heated water for heating an inhabitable enclosure.

616 Hot air furnace:
. Apparatus wherein the heater is a device which has an additional function of providing heated air for heating an inhabitable enclosure.

617 With heat storage mass:
Apparatus which further includes a quantity of solid material which is heated by the fluent medium during periods when solar radiation is received and which, in turn, liberates its heat at other periods of time.

618 Phase change:
. Apparatus wherein the material undergoes change in state from solid to liquid or from liquid to solid. A thermal energy storage system comprising a germanium phase change material and a graphite container. A thermal energy storage system comprising a germaniumphase change material and a graphite container.

619 Specific chemical:
. Apparatus wherein significance is attributed to the elemental composition of the material.

620 Rocks or soil:
. Apparatus wherein the material includes a relatively hard naturally formed mass of mineral or petrified matter or earth.

621 Solar collector forms part of building roof:
Apparatus wherein the converting means is made an integral part of a structure which provides a top cover of a building.

622 Solar collector includes roof shingles or tiles:
. Apparatus wherein the structure includes a plurality of overlapping pieces of material laid in rows.

623 Solar collector supported on existing roof structure:
Apparatus wherein the converting means is completely mounted on a roof exterior of the building.

624 Rollable or foldable collector unit of nonrigid material:
Apparatus wherein the converting means is made of a pliable material which may be overlapped upon itself for storage.

625 Fluent medium is gas:
. Apparatus wherein the fluent medium is a gaseous substance.

626 Fluent medium is water:
. Apparatus wherein the fluent medium is water.

627 Foldable collector unit of rigid material:
Apparatus wherein adjacent parts of the converting means are made of inflexible material and are connected to each other, and having structure permitting the parts to be doubled upon themselves for storage.

628 Including means to utilize fluent medium from collector to heat interior of building:
Apparatus having a means by which the heat of solar radiation is transferred via the fluent medium to heat the space enclosed by a building.

629 With device to circulate air from room of building through collector:
. Apparatus which includes a machine to move air from the space enclosed by the building through the converting means.

630 Plural circulators:
. Apparatus which includes more than one machine.

631 Circulator located in collector:
. Apparatus wherein the machine is located within an enclosure for the converting means.

632 Circulator located in building:
. Apparatus wherein the machine is located within the building.

633 With fluent medium passage in floor or wall of room:
. Apparatus in which a conduit is provided in a floor or wall of a building, and the fluent medium is moved through the conduit for the purpose of heating the enclosed building space.

634 With means to convey fluent medium through collector:
Apparatus having means by which the fluent medium is moved through the converting means and in doing so absorbs heat to be transferred elsewhere.

635 Having evaporator and condenser sections (e.g., heat pipe):
. Apparatus having a closed conduit to convey the fluent medium between a section heated by solar radiation and a cooled section whereby it is caused to change from liquid to gaseous state because of the absorption of solar radiation and subsequently change back to its liquid state as the heat of the gas is dissipated in the cooled section.

636 Particular fluid:
. Apparatus wherein significance is attributed to a specific kind of fluent medium.

637 Gas:
. Apparatus wherein the fluent medium is a gas.

638 Thermosyphonic fluid circulation:
. Apparatus in which the fluent medium is a fluid which completely fills a closed circuitous conduit extending between a low and a high elevation, and having a first section which passes through the converting means whereby the fluent medium is heated and rises in the conduit from the low to the high elevation, and a second section wherein the heat of the fluent medium is dissipated causing the cooled medium to descend into the second section and return to the first section.

639 Liquid:
. Apparatus wherein the fluent medium is a liquid.

640 With storage tank for fluent medium:
. Apparatus having a container in which the fluent medium from the converting means is accumulated.

641 Having heat exchanger within storage tank:
. Apparatus which includes a device that transfers heat from one fluid to another fluid without mixture of the fluids and is positioned inside the container.

A.2. Abstract-based Search

A second, more targeted, patent dataset was generated based on an electronic search for relevant keywords in the abstracts of all patents granted since 1976 with file dates ending in 2002 (to avoid lag effects). This search was put together iteratively, so as to balance over counting with undercounting. Once the search was finalized and the dataset created, content analysis was performed on the resulting “abstract-based” dataset for each technology in order to eliminate irrelevant patents, thus ensuring that this dataset is the most refined dataset possible. In the case of PV, it was found that the class-based dataset was a more reliable measure of patenting activity and thus used the class-based set for the subsequent analyses.[5]

A.2.1. PV

The construction of the abstract-based search began by using the interview with Examiner Diamond. He indicated several keywords that he uses to search for prior art when evaluating PV patent applications: "solar," "photovoltaic," "photoelectric," "solar cell," "solar battery," "solar module, " and "solar panel." A second point of reference was the set of search terms used by Margolis and Kammen (1999).[6] They used the search string: "(photovoltaic or (solar and electri$))". Several iterations were then tried, including and excluding keywords and comparing the resulting set of patents to that obtained by the class-based search. The research team found that the only way to design an abstract-based search that would include a high proportion of the patents held by PV firms was by designing a very general search that would necessarily include a large proportion of irrelevant patents. The resulting search string used was:

(ABST/((photovoltaic OR solar) OR photoelectric)

This search yielded 13,913 patents.

The team then manually coded approximately 2,000 patents for years 1976, 1988, 1998, and 2000 to estimate the number of irrelevant patents and found that 52% to 82% of the patents each year were not relevant to PV. The main reason for this high count of irrelevant patents was that the term "photoelectric" picks up many patents in the electronics industry, particularly devices using photoelectrical sensors. This problem was larger in the latter years. Because a large number of PV patents used the term "photoelectric" but not "photovoltaic" or "solar," this search term had to be included. This study used the class-based search for the remainder of the analyses because the high number (> 50%) of irrelevant patents included in the abstract-based search made it less accurate a representation of PV patenting activity than the class-based search and because manually coding 14,000 patents was not feasible.

A.2.2. STE

As a starting point to construct a search string for solar-thermal electric, search terms suggested by Examiner Nguyen from the 12/17/04 interview were used. He suggested using the following key words:

1. "thermo-electric$,"
2. "solar power system," and
3. "solar energy system."

[5] This was due to the combination of a large set of PV patents and a large set of non-PV patents which were impossible to distinguish from PV using only keywords.

[6] Margolis, R. M. and D. M. Kammen (1999). "Evidence of Under-investment in Energy R&D in the United States and the Impact of Federal Policy." *Energy Policy* **27**: 575–584.

To expand the set of relevant patents the three terms above were combined with other characteristics of STE technology, e.g. “steam,” “thermal,” “heat exchanger,” and “heat engine.” The following search maximized the count of relevant patents.

ABST/((solar AND (electric$ OR power)) AND ((steam OR thermal) OR heat))

Researchers then read each patent abstract to discard from the set any patents not relevant to STE technology. The final set yielded 615 patents.

A.2.3. SWH

In the interview with Examiner Price, he suggested that the research team use the concept of temperature to identify SWH patents. He also warned that it would be difficult to identify key words that would be appropriate for SWH without also picking up irrelevant patents. Since the study’s methodology includes a manual reading of all patent abstracts, picking up these irrelevant patents would not be a problem. Researchers used search terms that characterize solar water heating technology and included exclusion terms to avoid picking up PV and pool heater patents:

ABST/(((solar AND ((hot OR heat) OR thermal)) AND (water OR fluid)) ANDNOT ((electric OR cell) OR pool))

Researchers then read each patent abstract to discard from the set any patents not relevant to STE technology. The final set yielded 1070 patents.

A.3. Patent Citation Rates

The class-based and abstract-based datasets described above provide measures of overall patenting activity, but they do not distinguish among patents based on the *quality* of the inventions these patents represent. Several metrics have been devised in the economics of innovation literature to cope with patent quality, including citation frequency, the relative number of claims contained in a patent, and the commercial value of a patent as represented by the payment of periodic fees by patent-holders to maintain the monopoly rights to their patents over time.

This report focuses on the citation rate as a basic metric for patent quality. This means that a metric is developed based on the number of times that a patent has been referenced as legal “prior art” by other patents. Studies have shown that highly cited patents tend to be the most economically valuable (Harhoff et al. 1999).[7]

To develop the citation rate metric, researchers captured the number of citations each patent received from all other patents in the USPTO dataset. As it typically takes about ten years for a patent to receive most of its citations, later patents have less potential citations than earlier patents. As an example, a patent issued in 1997 and granted in 1999 will not have met its full citation “potential” by 2001, the year our dataset ends. An

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[7] Harhoff, D., F. Narin, et al. (1999). "Citation Frequency and the Value of Patented Inventions." *The Review of Economics and Statistics* **81**(3): 511–515.

important limitation for this study is that citation data is only available for patents granted before 2000. Given the application lag of two years before a filed patent is typically granted and the citation truncation effects just mentioned, this means that patents applied for after 1994 have do not have full citation data.

Appendix B

Interviews with Experts

Appendix B: Interviews with Experts

B.1. Expert Selection Procedure

The first step in the expert selection process was to analyze the annual American Solar Energy Society (ASES) Solar Conference proceedings from 1975 through the most recent year available]. These symposia covered solar photovoltaic (PV), solar thermal electric (STE) and solar hot water (SHW) technologies. In order to focus this analysis on specific technology categories, researchers coded papers, based on their titles and abstracts, as relevant or not. From the relevant subset of papers, researchers obtained the distribution of authors presenting papers according to the type of organizations they represented. This distribution was used to suggest a likely distribution of expert affiliation types that should be represented in the interviews. Researchers then ranked authors by the number of conferences at which a paper they had co-authored was presented, or at which they had chaired a conference session. Based on these rankings, thirteen individuals in each of the three categories were targeted for interviews.

For each of the three solar categories, researchers added 5 or 6 prospects in addition to the aforementioned network analysis. Most of these prospects were recommendations of the other individuals we contacted (whether interviewed or not), as selected through the process described above. Of all the interviews completed, only 1 PV interview came from this additional list of prospects.

B.2. Interview Method

All interviews except one were conducted by phone and were designed for subjects to exit the interview after an hour with an abbreviated interview, or choose to continue and participate in a full interview. The exception was one PV interview conducted in person. Once phone interviewees agreed to participate in the study, they were sent a preliminary email that contained a large attachment with several items. These included: an informed consent form; blank graphs for the interviewees to sketch trends in capital costs, and technology, R&D funding over time (these graphs primarily serve as memory jogs for the interview subjects as well as a way to calibrate responses across experts), a fax cover sheet to expedite the return of materials prior to the interview, and a list of government actions and a sketch of patenting activity over time.[1,2,3] Subjects were asked not to look at

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[1] Blank graphs for PV interviews

- market cost of technology in $/W vs. time
- efficiency gains over time in PV cell efficiency vs. time

[2] Blank graphs for STE interviews

- market cost of technology in cents/kWh vs. time
- efficiency gains over time in system efficiency vs. time

[3] Blank graphs for SHW interviews

- market cost of technology in $/ft.vs. time
- system lifetime changes over time in system lifetime vs. time

the list of government actions and patent sketch until prompted to do so in the interview; when this was not heeded, an additional question was added to the end of the interview protocol.

Appendix C

Conference Analysis Procedures

Appendix C: Conference Analysis Procedures

C.1. Procedures in Common

C.1.1. Coding

For each year of the conference, researchers first determined what the sessions were. Each paper received a unique number for that year. The order was chronological, determined by the session key.

For each year of the conference, researchers created a worksheet in Microsoft Excel outlining the following information: the author(s) of the paper, the author's organization, an affiliation type for that organization, the location of that organization, a code for that location, the title of the paper, the session that the paper was presented in and a unique paper number for that year.

In addition, each paper was also coded by technology type: Photovoltaic (PV), Solar Thermal Electric (STE), Solar Water Heating (SHW), "All Solar" (All), or not technology relevant (NOT). The NOT papers were removed from the analysis. For the technology specific sections of this analysis, researchers looked at only the SHW-, STE-, and PV-coded papers. The "All" category were papers that were not-specific to any one technology and relevant to the entire industry. These ALL papers were thus also removed from the dataset. Coding by technology occurred by looking at the session titles when available, and then the abstracts of the papers.

If there were multiple authors for one paper, each author received his/her own separate entry line in Excel with the relative organizational information but using the same paper identification information. That way, if an author from a firm co-authored a paper with a different author in government, it would be clear that two people wrote the same paper even though their entries are on different lines.

C.1.1.1. Location

The author's organization's location data was obtained by first looking at the paper to see if an address is given. If not, researchers looked to see if it was given in a different paper from the same year. If not available, researchers would look at the attendee list if one was available. If location data was not available for that author for that year, researchers looked to see if other members of that organization presented that year, and if a location was given in that case. Researchers also looked to see if a location was available for the author in other years. If all of these methods failed, researchers looked up the organization's website to try and find contact info. If the organization did not have a website or was not listed in any available directories, the location was marked as unknown.

Each location was subsequently coded "CA," "US," or "International." If the entry was International, a separate column was created that would specify the country of origin. From there, researchers could perform counts on each code to determine proportions between the three.

C.1.2. Author Data Cleaning

Each year was entered on a separate worksheet in Microsoft Excel. After each year was entered, researchers combined them onto a Master Worksheet. The data were equalized, making uniform entries across the years. For example, researchers made “Smith, John” the same as “Smith, John Q.” and “Smith, J.Q.” This was done for authors, affiliations, and locations. Researchers cleaned this data so that the count function in Microsoft Excel could be used.

C.1.3. Counts

After the data were combined and equalized, researchers used the count function in Microsoft Excel to see how many unique times that entry existed. Researchers also performed straight counts of Affiliation type, location codes, and international countries. For the author count, a second manual count was done to determine unique conferences presentations. Meaning, if “Smith, John Q.” had a count of four, but only at two unique conferences, his count was lowered to two. Researchers then performed a count of the counts, in order to determine how many authors like “Smith, John Q.” had written papers at two unique conferences.

C.2. Notes Specific to the ASES Conference Analysis

C.2.1. Obtaining Proceedings

The long-standing history of the ASES conference created a challenge for collecting all of the conference proceedings. The history of the conference is over 50 years; some conference papers were published in the Solar Journals in the 1950s-60s while later proceedings were then subsequently published in a separate text. All of the proceedings were collected either at the Berkeley Library or via Inter-Library loan. Note: The conference is mostly continuous with the exception of no conference in 1985 or 1991. Besides the 1955 conference, all of the papers presented in the conferences before 1976 were presented in the AFASE-sponsored journal *Solar Energy*. Due to the anemic nature of the society at the time, there were much larger lags in the publishing of these papers than the rest of the time series.

Table C.1. Issues of *Solar Energy* that conference proceedings are located

Volume	*Number*	*Year*
1	2	1957
1	3	1957
9	1	1965
9	3	1965
9	4	1965
10	1	1966
10	2	1966
10	3	1966
10	4	1966
11	1	1967
11	2	1967
12	1	1968
12	2	1968
14	1	1972
14	2	1973
14	3	1973
14	4	1973
15	1	1973
15	2	1973

Particular care was taken to make certain that only conference proceedings and not journal articles that were also published in the journal.

With respect to the 1985 and the 1991 conference, the national ASES symposium was not held in lieu of other conferences sponsored by the society. These conferences were different enough from the normal ASES conference to not be included in the dataset.

C.2.2. Location of Conference

The ASES Conference is an American sponsored conference. Table C.2 below shows the location of the conferences held from 1955–2004.

Table C.2. Locations of ASES conferences, 1955–2004

Year	*Location*	*Year*	*Location*
1955	Tucson, AZ	1986	Boulder, CO
1957	Phoenix, AZ	1987	Portland, OR
1959	New York, NY	1988	Cambridge, MA
1965	Phoenix, AZ	1989	Denver, CO
1966	Boston, MA	1990	Austin, TX
1967	Tempe, AZ	1992	Cocoa Beach, FL
1968	Palo Alto, CA	1993	Washington, DC
1971	Washington, D.C.	1994	San Jose, CA
1976	Winnipeg, Canada	1995	Minneapolis, MN
1977	Orlando, FL	1996	Asheville, NC
1978	Denver, CO	1997	Washington, DC
1979	Atlanta, GA	1998	Albuquerque, NM
1980	Phoenix, AZ	1999	Portland, ME
1981	Philadelphia, PA	2000	Madison, WI
1982	Houston, TX	2001	Washington, D.C.
1983	Minneapolis, MN	2002	Reno, NV
1984	Anaheim, CA	2003	Austin, TX
		2004	Portland, OR

C.2.2.1 Title and Dates of the Conference

All of the conferences, their locations, the dates they were held and the number of papers presented for each conference are located in Table C.3.

Table C.3. Location, title and number of papers of ASES conferences, 1955–2004

Year	*Title*	*Dates*	*Location*	*# of Papers*
1955	Transactions of the Conference on the Use of Solar Energy: The Scientific Basis	October 31–Nov. 1	Tucson, AZ	86
1957	Solar Furnace Symposium	January 21–22	Phoenix, AZ	20
1959	Advisory Council Association for Applied Solar Energy	May 26–28	New York, NY	17
1965	Solar Energy Society Annual Meeting	March 15–17	Phoenix, AZ	62
1966	Annual Meeting	March 21–23	Boston, MA	43
1967	Third Annual Meeting of Solar Energy Society	March 20–22	Tempe, AZ	29
1968	SES Annual Meeting	October 18–23	Palo Alto, CA	40
1971	1971 Conference	May	Washington, D.C.	50
1976	Sharing the Sun! Solar technology in the Seventies	August 15–20	Winnipeg, Canada	332
1977	1977 Annual Meeting American Section of the International Solar Energy Society	June 6–19	Orlando, FL	252
1978	1978 Annual Meeting of the American Section of the ISES: Solar Diversification	August 28–31	Denver, CO	323
1979	SUN II: Silver Jubilee Congress and Meeting of the AS/ISES	May	Atlanta, GA	544
1980	Solar Jubilee: 25 Years of the Sun at Work: The 1980 Annual Meeting of the AS/ISES	June 2–6	Phoenix, AZ	314
1981	Solar Rising: The 1981 Annual Meeting of the AS/ISES	May 26–30	Philadelphia, PA	331
1982	The Renewable Challenge: 1982 Annual Meeting		Houston, TX	234
1983	1983 Annual Meeting	May 29–June 3	Minneapolis, MN	24[1]
1984	ASES '84	June 5–7	Anaheim, CA	120

[1] Only the presented papers were available for this year.

Year	Title	Dates	Location	# of Papers
1986	ASES '86	June 11–14	Boulder, CO	112
1987	Solar '87: Annual Meeting	July 11–16	Portland, OR	98
1988	Solar '88: The Annual Meeting of the American Solar Energy Society	June 20–24	Cambridge, MA	100
1989	Solar '89: The National Solar Energy Conference	June 19–22	Denver, CO	97
1990	Solar 90: The National Solar Energy Conference	March 19–22	Austin, TX	93
1992	Solar '92: Bright Star for the Blue Planet	June 15–18	Cocoa Beach, FL	92
1993	Solar '93: Solar Emerging The Reality	April 25–28	Washington, D.C.	97
1994	Solar '94	June 27–30	San Jose, CA	82
1995	Solar '95: 10,000 Solutions: Paths to a Renewable Future	July 15–20	Minneapolis, MN	66
1996	Solar '96 Conference	April 13–18	Asheville, NC	69
1997	1997 Annual Conference	April 25–30	Washington, D.C.	58
1998	Solar '98	June 14–17	Albuquerque, NM	92
1999	Solar 99 Conference	June 12–16	Portland, ME	74
2000	Solar2000	June 16–21	Madison, WI	71
2001	Forum 2001 - Solar Energy: The Power to Choose	April 21–25	Washington, D.C.	76
2002	Solar 2002: Sunrise on the Reliable Energy Economy	June 15–20	Reno, NV	74
2003	Solar 2003: America’s Secure Energy	July 21–26	Austin, TX	86
2004	Solar 2004: A Solar Harvest Growing Opportunities	July 11–14	Portland, OR	104

C.2.2.1. Sponsorship of the Conference

The American Solar Energy Society (and its pre-cursors) is the primary sponsor of the conference each year. Various government organizations, universities, and firms have co-sponsored the conference over time. Table C.4 shows the sponsorship over time of the conference. The most prominent co-sponsors of the conference are the U.S. Department of Energy and the Solar Energy Research Institute. Various other associations also sponsored for a single year. Generally, these sponsorships have to do with the location of the conference of that year.

Table C.4. Sponsorship information of the ASES conferences, 1955–2004

Year	***Sponsorship***	***Year***	***Sponsorship***
1955	University of Arizona; Stanford Research Institute; Association for Applied Solar Energy	1986	Colorado Office of Energy Conservation; SERI; Western Area Power Administration; AIA of Colorado; Arizona Society of Architecture/AIA; Boulder Energy Conservation Center; Boulder County Commissioners; Boulder County Department of Public Works; Denver Solar Energy Association; Home Resource Magazine; New Mexico Society of Architecture/AIA; Nebraska Society of Architecture/AIA; Solar Age Magazine; Utah Society/AIA; Wyoming Chapter/AIA
1957	*	1987	AIA Portland Chapter; ASME; Bonneville Power Administration; City of Portland; City of Ashland; EPRI; Emerald PUD; Energy Mines and Resources in Canada; Eugene Water and Electric Board; Illuminating Engineering Society, Oregon Section; Lawrence Berkeley National Lab; League of Oregon Cities; NW Power Planning Council; Oregon Department of Energy; Oregon State University; Pacific Power and Light; Portland Energy Conservation, Inc.; Portland General Electric; Puget Power; Salem Electric; SERI; University of Oregon US DOE; VBB Allen; Viking Industries; Washing State Energy Office

Year	*Sponsorship*	*Year*	*Sponsorship*
1959	AFASE; New York University; Stanford Research Institute	1988	Massachusetts Executive Office of Energy Resources; Massachusetts Photovoltaic Center; Associated Weather Services; Massachusetts Institute of Technology; Mobil Solar; American Meteorological Society; ASME Solar Division; Boston Edison Company; Massachusetts Horticultural Society; National Association of Homebuilders; New England Electric System; Northeast Utilities; SERI; Union of Concerned Scientists; U.S. Department of Energy
1965	*	1989	ASES; Western Area Power Administration; Colorado Office of Energy Conservation; SERI; Public Service Company of Colorado
1966	*	1990	Lower Colorado River Authority; Texas Governor's Energy Management Center; City of Austin Electric Utility Department; University of Texas at Austin; 3M Solar Optical Products Group; West Texas State University (AEI); City of Austin, Energy Design Assistants; GSD&M Advertising; General Motors Corporation; Luz Development and Finance Corporation; National Energy Foundation; Passive Solar Industries Council; Planergy Inc; Sierra Club; Teas Department of Agriculture; Texas Department of Commerce
1967	*	1992	Florida Solar Energy Center; U.S. Department of Energy; Florida Energy Office
1968	*	1993	U.S. Department of Energy

Year	***Sponsorship***	***Year***	***Sponsorship***
1971	NASA	1994	U.S. Department of Energy; City of San Jose
1976	AS/ISES and Solar Energy Society of Canada	1995	U.S. Department of Energy
1977	U.S. Energy Research and Development Administration (ERDA)	1996	U.S. DOE; Carolina Power and Light; Community Foundation of Western North Carolina; Duke Power Company; Energy Division of North Carolina Department of Commerce; North Carolina Alternative Energy Corporation; North Carolina Solar Center; Rays of Hope; Tennessee Valley Authority
1978	Solar Energy Industries Association; SERI; Colorado Solar Energy Association; Colorado Energy Research Institute; University of Delaware	1997	US Department of Energy
1979	*	1998	US DOE; Organization of American States; Sandia National Labs; University of New Mexico; NationsBank; New Mexico Land Office; Public Service Company of New Mexico; New Mexico Energy Office
1980	Arizona Solar Energy Association; Arizona Solar Energy Commission; Solar Energy Industries Association; SERI; University of Delaware; Western Solar Utilization Network	1999	U.S. Department of Energy
1981	Franklin Research Center; National Association of Home Builder's Research Foundation, Inc.; National Solar Information Center; Pennsylvania Region I Resource Center; SERI; U.S. DOE; University of Delaware; Western Solar Utilization Network	2000	U.S. Department of Energy

Year	*Sponsorship*	*Year*	*Sponsorship*
1982	U.S. Department of Commerce; Texas Energy and Natural Resources Advisory Council; Houston Lighting and Power Company; University of Houston Energy Laboratory; Progressive Architecture; Houston Chamber of Commerce; Atlantic Richfield Company; Texas Solar Energy Society; Houston Solar Energy Society; Solar Age; University of Delaware; Phillips Petroleum Company	2001	U.S. Department of Energy
1983	*	2002	U.S. Department of Energy
1984	*	2003	U.S. Department of Energy
		2004	U.S. Department of Energy

For all of the years marked with an * in Table C.4, sponsorship information was not available on the proceedings. This is particularly true with the CD-ROM versions (1999–2004) that were available to be analyzed.

C.2.3. Session Keys

Each conference is broken down into various paper sessions. Some sessions continue year to year while others change over time to reflect topics of particular interest at the time. Session keys were not specified for the year 1957 and thus are not included in this particular analysis. The session titles were also cleaned, making “Collector Design” the same as “Design of Collectors,” for example. Omitted from the session titles conference are gatherings like “keynote” and “opening session” and “awards.” Table C.5 shows a sample of the session titles and the years they were presented. From 1955–2004, there were 675 identified sessions presented in the conferences.

Table C.5. Session titles, frequency, and year at ASES conferences, 1955–2004

Session Focus	*Number of Conference Appearances*	*ASES Conferences Appearances and Notes*
Active Solar	3	1992–94
Architecture	4	1981–84
Collector Design	2	1987–88
Cooling	2	1977–78
Hot Water	5	1978, 1987–88, 1990, 2002
Economics	11	1965, 1976–78, 1980–82, 1987, 1993, 1999, 2000
Education	9	1976, 1986–87, 1989, 1990, 1992–94, 2000
Engineering	4	1980–1982, 1986
Low Temperature	4	1966, 1999, 2001, 2003
Passive Systems	8	1976–79, 1980–84,
Photovoltaic	14	1976, 1978, 1987–88, 90, 93–97, 99, 2001–04
Resource Assessment	7	1992, 1994, 1997–1999, 2000–01
Solar Distillation	4	1959, 1968, 1971, 2002
Solar Electric	4	1971, 1989, 1990, 1992
Solar Radiation	10	67, 78, 79, 82–4, 86–88, 93,
Solar Thermal	11	1976, 1978, 88–90, 1993–94, 97, 2000, 2003–04

C.2.5. Affiliation Codes

The research team coded all of the affiliations by Association, Contract nonprofit R&D, Firm, Government, Utility, and University. Researchers were able to assign an affiliation code to all affiliations—none needed to be removed.

C.2.6. Location Codes

Each of the papers were coded by the location of the author's affiliation's location. When coded international, the country of origin was listed. The top international contributors are listed in the main report but the full list is located below by technology

C.2.6.1. International - PV

Of the 197 papers that were coded International, those countries that were less than 7% were not specified in the main report. The full list is located here, with the number of papers from each country and the percentage of the international contribution also shown in Table C.6.

Table C.6. International PV papers

Country	# of Papers	% of International Contribution
Canada	29	15
Spain	24	12
Mexico	13	7
Russia	13	7
Egypt	12	6
France	11	6
The Netherlands	10	5
Germany	9	5
India	9	5
United Kingdom	8	4
Australia	7	4
China	7	4
Italy	7	4
Japan	6	3
Iran	5	3
Korea	4	2
Argentina	3	2
Israel	3	2
Saudi Arabia	3	2
Portugal	2	1
Sweden	2	1
Tuvalu	2	1
Venezuela	2	1
Belgium	1	1
Jordan	1	1
Nigeria	1	1
Norway	1	1
Sri Lanka	1	1
Tahiti	1	1
Total	197	100%

C.2.6.2 International – STE

Of the 200 papers that were coded International, those countries that were less than 10% were not specified in the main report. The full list is located here, with the number of papers from each country and the percentage of the international contribution also shown in Table C.7.

Table C.7. International STE papers

Country	# of Papers	% of International Contribution
France	34	17
Japan	23	12
Mexico	19	10
Italy	19	10
Germany	16	8
Canada	14	7
Korea	10	5
Australia	8	4
Israel	7	4
Egypt	7	4
Brazil	7	4
Spain	5	3
Kuwait	5	3
Russia	3	2
Romania	3	2
Algeria	3	2
United Kingdom	2	1
Ukraine	2	1
Taiwan	2	1
Nicaragua	2	1
India	2	1
Czech Republic	2	1
China	2	1
Yugoslavia	1	1
The Netherlands	1	1
Saudi Arabia	1	1
Grand Total	200	100%

C.2.6.3 International – SHW

Of the 332 papers that were coded International, those countries that were less than X% were not specified in the main report. The full list is located here, with the number of papers from each country and the percentage of the international contribution also shown in Table C.8.

Table C.8. International SHW papers

Country	# of Papers	% of International Contribution
Canada	102	30.7
France	26	7.8
Germany	20	6.0
Italy	20	6.0
Australia	19	5.7
Japan	19	5.7
India	15	4.5
Mexico	15	4.5
The Netherlands	15	4.5
Sweden	11	3.3
United Kingdom	11	3.3
Israel	9	2.7
Brazil	5	1.5
Korea	4	1.2
Portugal	4	1.2
Taiwan	4	1.2
Denmark	3	0.9
South Africa	3	0.9
West Indies	3	0.9
China	2	0.6
Kuwait	2	0.6
Panama	2	0.6
Saudi Arabia	2	0.6
Switzerland	2	0.6
Turkey	2	0.6
US	2	0.6
Belgium	1	0.3
Chile	1	0.3
El Salvador	1	0.3
Finland	1	0.3
Iran	1	0.3
Jamaica	1	0.3
Libya	1	0.3
Malaysia	1	0.3
Monaco	1	0.3
Senegal	1	0.3
Total	332	100.0